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SAFE DISTANCES FROM UNDERWATER EXPLOSIONS FOR MAMMALS AND BIRDS

John T. Yelverton, et al

Lovelace Foundation for Medical Education and Research

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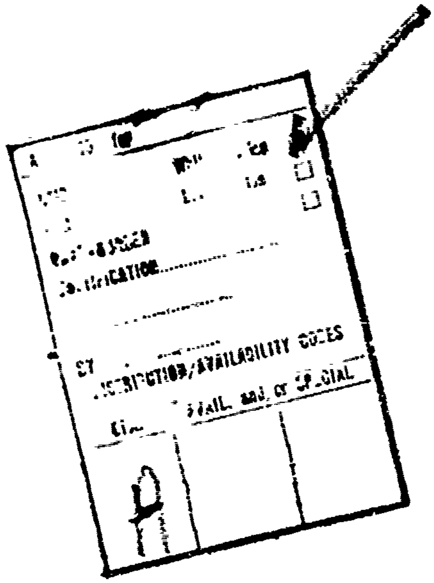
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Tests were run to determine the far-field underwater blast effects on mammals and birds. The tests were conducted in a specially constructed test pond facility, 220 by 150 feet at the surface and 30 feet deep over the 30- by 100-foot center portion. Explosive charges weighing up to 8 pounds were detonated at 10-foot depths.

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20. ABSTRACT (Continued).

Sheep, dogs, and monkeys were suspended in the water, mostly with their long axis perpendicular to the surface at 1-, 2-, and 10-foot depths. The duck was selected as a model to represent birds on the surface and birds that dive beneath the surface. Ducks were tested on the water surface and at 2-foot depths.

The nature of the immersion-blast injuries was described and related to the impulse measured in the underwater blast wave. Impulse levels which were safe and which produce injuries in mammals and birds were presented.

Underwater-blast criteria were presented which corresponded to safe and damaging impulse levels for birds and mammals along with curves relating the impulse criteria as a function of range and charge weight.

PREFACE

This report presents the results of tests run to determine the effects of underwater explosions on birds and mammals. The information should be of interest to government agencies and private industry groups desiring to prepare Environmental Impact Statements in connection with detonating high explosives in a water environment.

The studies involving mammals were supported by the U.S. Navy Bureau of Medicine and Surgery under the direction of the Explosions Research Department, U.S. Naval Ordnance Laboratory, under contract with the Defense Nuclear Agency. Contract No. DASA-01-71C-0013.

The investigations on bird response to underwater shock were supported by the Defense Nuclear Agency, STMD, Contract No. DASA-01-70C-0075.

This research was conducted according to the principles enunciated in the "Guide for Laboratory Animal Facilities and Care," prepared by the National Academy of Sciences, National Research Council.

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INTRODUCTION

The purpose of this paper was to present the results of two recent studies which provided information on the response of mammals and birds to underwater explosions. One of the studies determined the far-field immersion-blast effects in sheep, dogs, and monkeys. The animals were subjected to underwater blast with their heads above the surface and at 2- and 10-foot depths. Although the study was run with terrestrial mammals and was aimed at establishing safe ranges for swimmers, the results were applied in this paper to formulate underwater-blast criteria for aquatic and marine diving mammals.

The other study determined the response of birds to underwater blasts while on the surface and at 2-foot depths. The duck was chosen as a model to represent swimming and diving birds. Blast criteria were derived which related underwater-blast impulse levels that were safe, that produced injuries, and that were lethal for birds on and beneath the water surface. Graphs were presented giving the slant ranges from underwater explosions associated with the impulse criteria levels as a function of charge weight, depth of burst, and depth of the biological specimens.

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METHODS

The Test Pond

The test pond measured 220 by 150 feet at the water surface and was 30 feet deep over its 30- by 100-foot center portion, Figures 1 and 2. The entire pond was lined with black polyvinyl plastic 20 mils thick. A 6-inch-deep layer of sand was located beneath the plastic in the 30-foot-deep part of the bottom. The sides of the pond had a 2-to-1 slope. Two sets of rigging spanned the pond in a north-south direction. The main rigging, located 80 feet from the west end, consisted of a grid 14 by 24 feet which could be raised and lowered by cables on the south bank. The other rigging was 30 feet from the east end of the pond and had a 5- by 10-foot grid. It was raised and lowered by a hand-operated winch on the south bank. The test pond contained approximately 3.2 million gallons of tap water.

The ambient air pressure at the test pond was 12.0 psia.

Explosive Charges

The explosive charges used in these experiments were bare spheres of cast Pentolite and TNT and 1-pound blocks of pressed TNT. The charges had 5/16-inch-diameter detonator wells. The charges were fired with electric blasting caps, DuPont No. E-99. The charge weights were designated as 0.5 pound, 1 pound, 3 pounds (actually 2.6 pounds), and 8 pounds.

Pressure-Time Measurements

There were four channels of pressure-time measuring instrumentation. The methods and equipment used for measuring and recording the underwater blast wave basically were those described in references 1 and 2. The pressure-time gauges were a recent modification of the NOL gauge, Type B. Sensing elements of the gauges consisted of four 1/4-inch-diameter tourmaline discs mounted in a Tygon[5] tube filled with silicone oil (Dow-Corning No. 200 dielectric oil). Signals from the gauges were passed through a cathode-follower K amplifier unit and recorded on a dual-beam oscilloscope (Tektronix Model 555 with Type D preamplifier plug-in units). To ensure accurate time measurements, timing marks were placed on the oscilloscope with a time-marker generator.

Figure 1. Underwater test facility viewed from the west.

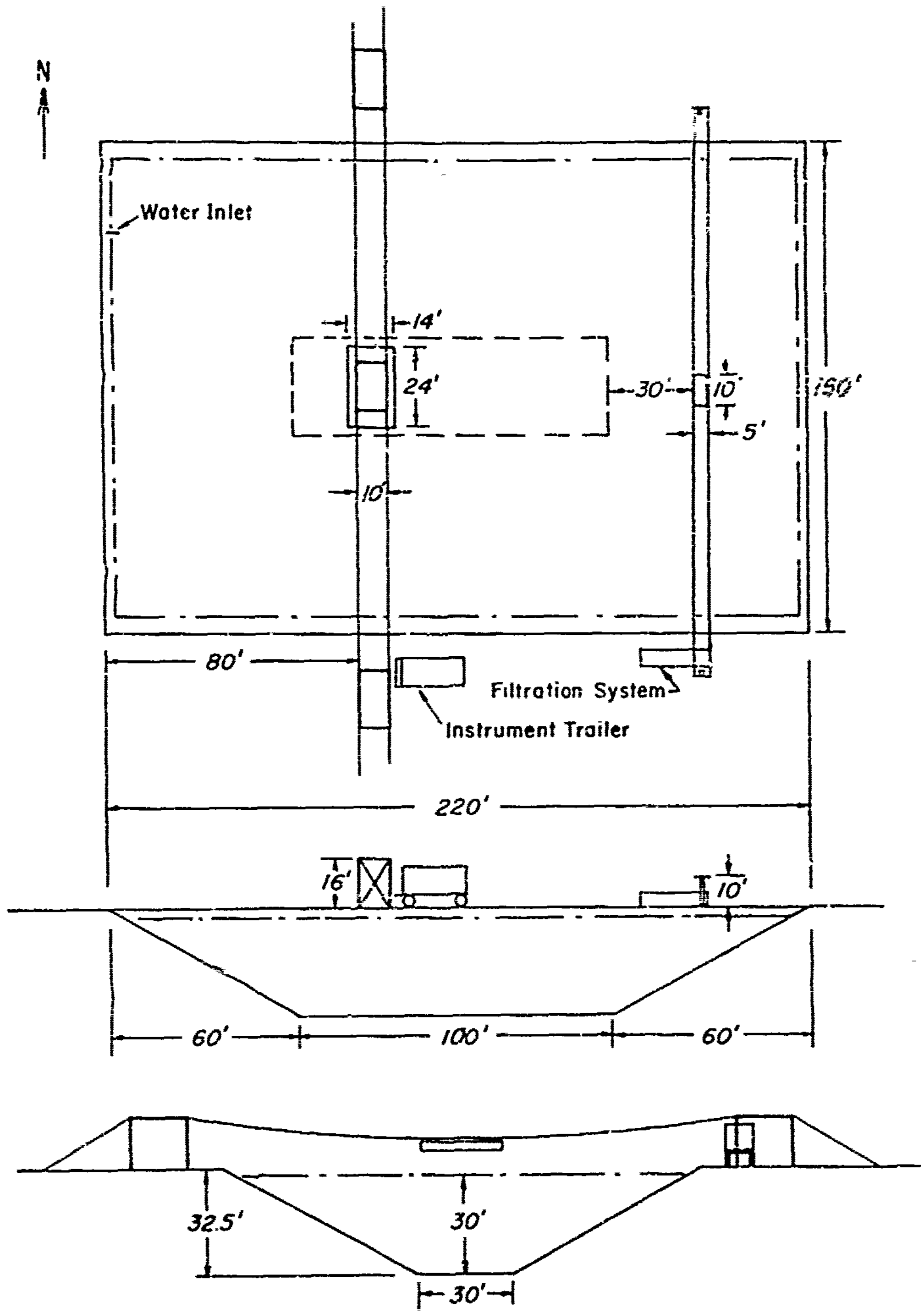


Figure 2. Diagram of underwater test facility.

On each trial, recording gauges were placed at the same ranges as the mammals or birds and at their designated depths. The only exception to this routine was on the two shots where targets were at 0.5-foot depths with the gauges at 1-foot depths. Attempts were made to locate the gauges away from the animals so that the subjects themselves would not alter the pressure-time pattern. Trigger gauges were located just upstream from the recording gauges so that their signals would initiate the sweep of the oscilloscope.

The system was calibrated by the voltage-step method. A voltage-step generator supplied a known voltage impulse to the system. The calibration voltage step and time markings were placed on separate oscillograph records immediately before each test.

Pressure recordings were enlarged photographically, and semilogarithmic plots made for each one. Pressure values were obtained from the curves by the following equation:

$$P = \frac{C_s E_c}{KA} \frac{\Delta P}{\Delta V} \qquad (1)$$

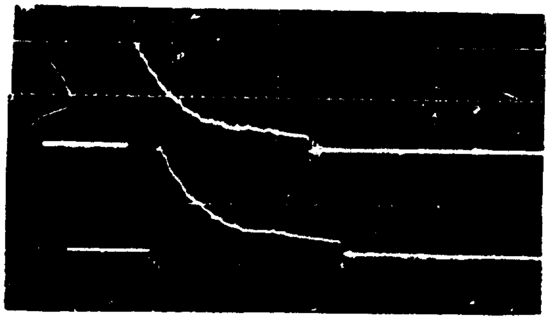
where
- P = pressure, psi
- C_s = standard capacitance, microfarads
- E_c = calibration voltage, volts
- ΔP = deflection on record due to pressure
- ΔV = deflection on record due to calibration
- KA = gauge sensitivity, coulombs x 10^{-12}

The KA of the gauges was determined at NOL.

A computer program was developed to extrapolate the pressure curve back to one-half the rise time to obtain the peak pressure. This added area under the curve was included in the integration for the impulse. The theta and energy parameters likewise were calculated by the computer.

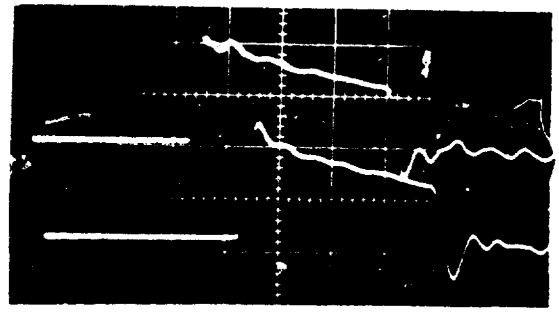
Incident Shock Waves

Pressure-time records showing the pattern of the incident shock waves at selected ranges are illustrated in Figure 3. These records show that there is little left to be desired from the NOL underwater gauges which have the



Shot No.: 188 Slant Range: 13 ft

Gauge No.	Vertical Scale	Horiz. Scale
3257	565 psi/div	0.1 msec/div
3412	571 psi/div	0.1 msec/div



Shot No.: 199 Slant Range: 60 ft

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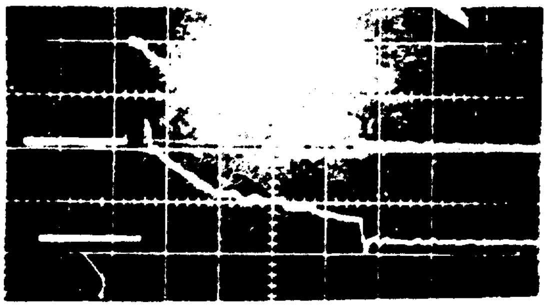
3264	100 psi/div	0.02 msec/div



Shot No.: [illegible] Slant Range: 20 ft

Gauge No.	Vertical Scale	Horiz. Scale
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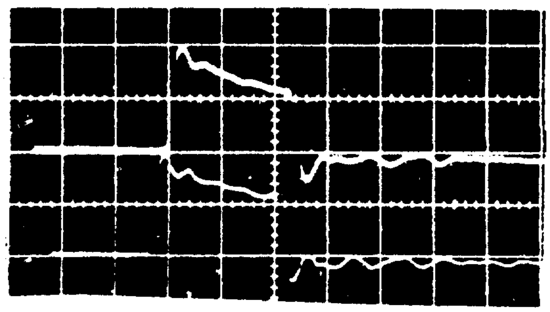
[illegible]	[illegible] psi/div	0.05 msec/div



Shot No.: 209 Slant Range: 78 ft

Gauge No.	Vertical Scale	Horiz. Scale
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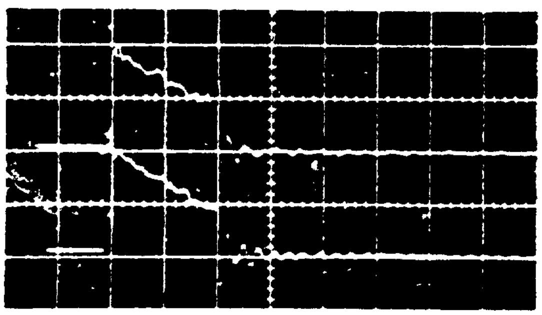
3412	73 psi/div	0.02 msec/div



Shot No.: 204 Slant Range: 40 ft

Gauge No.	Vertical Scale	Horiz. Scale
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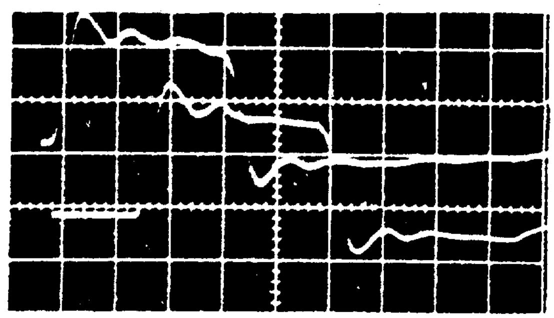
3412	158 psi/div	0.05 msec/div



Shot No.: 193 Slant Range: 130 ft

Gauge No.	Vertical Scale	Horiz. Scale
3257	43 psi/div	0.01 msec/div
3412	43 psi/div	0.01 msec/div

Figure 3. Oscillograms of incident shock waves recorded by gauges at 1-foot depths when 1-pound charges were detonated at 10-foot depths.

tourmaline crystals inside a Tygon® tube filled with silicone oil. The mean values for peak pressure, impulse, and cut-off time, measured at 1-foot depths on the 1-pound Pentolite charge firings, are plotted in Figure 4 in relation to slant range. The curves in Figure 4 are those calculated from these empirically derived equations:

$$P_m = 18300 \left(W^{1/3}/R\right)^{1.10} \tag{2}$$

$$\theta = 0.0603 \left(W^{1/3}/R\right)^{-0.168} W^{1/3} \tag{3}$$

$$t_c = \left(\sqrt{R^2 + 4\, D_w D_g} - R\right)/C_o \tag{4}$$

$$I = P_m \theta \left[\frac{9}{11}\left(1 - e^{-\frac{11 t_c}{10\theta}}\right) + 1 - e^{-\frac{t_c}{10\theta}} \right] \tag{5}$$

where W = charge mass, pounds; R = slant range, feet; t_c = time of arrival of the surface cut-off wave, msec; θ = time constant, msec; P_m = peak over-pressure, psi; I = impulse to cut-off time, psi·msec; D_w = depth of charge, feet; D_g = depth of gauge, feet; and C_o = speed of sound in water, 4.75 feet/msec.

As seen in Figure 4, the measured data points for peak pressure, impulse, and cut-off time fell closely along the calculated curves. Moreover, there was little variation in the values measured by different gauges on a given shot in regard to peak pressure, impulse, and cut-off time.

Negative Pressures

The peak negative pressures were read from the records from the pre-shock baseline to the maximum deflection the trace went below baseline. The mean peak negative pressures on each shot are plotted in Figure 5 in relation to scaled slant range. The magnitude of the negative pressures decreased with increasing slant range. They ranged from 110 to 150 psi at scaled ranges of 13 and 16 feet to 20 to 25 psi at scaled ranges of 140 feet. The negative pressures were of short duration--on the order of 10 μsec--which, in terms of the frequency response of gauges, could account for some of the scatter in these measurements. There was fair agreement between the points measured in this study and the curve

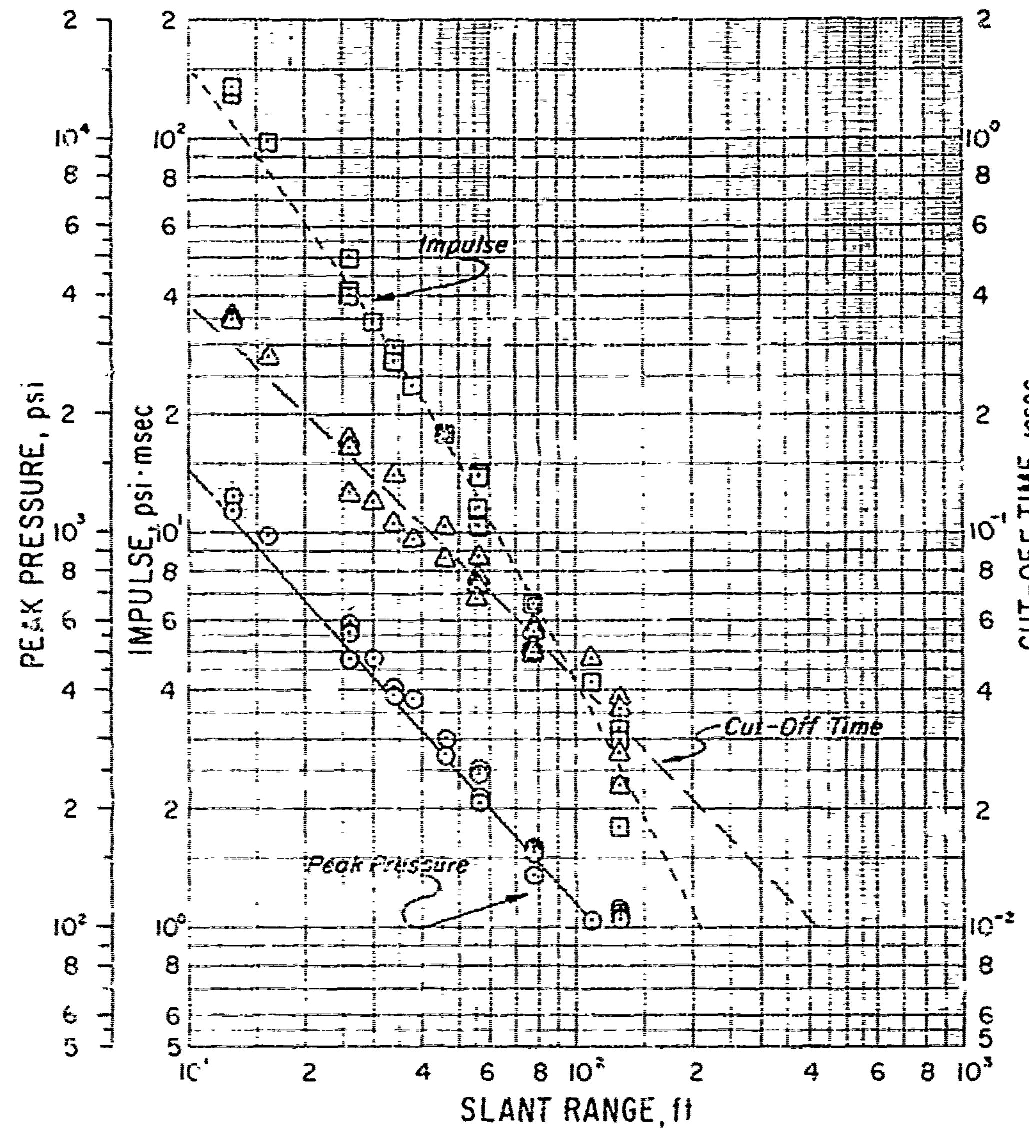


Figure 4. Pressure-time parameters in the incident shock wave at 1-foot depths as a function of range from 1-pound Pentolite charges detonated at 10-foot depths. [The data points were measured; the curves were computed.]

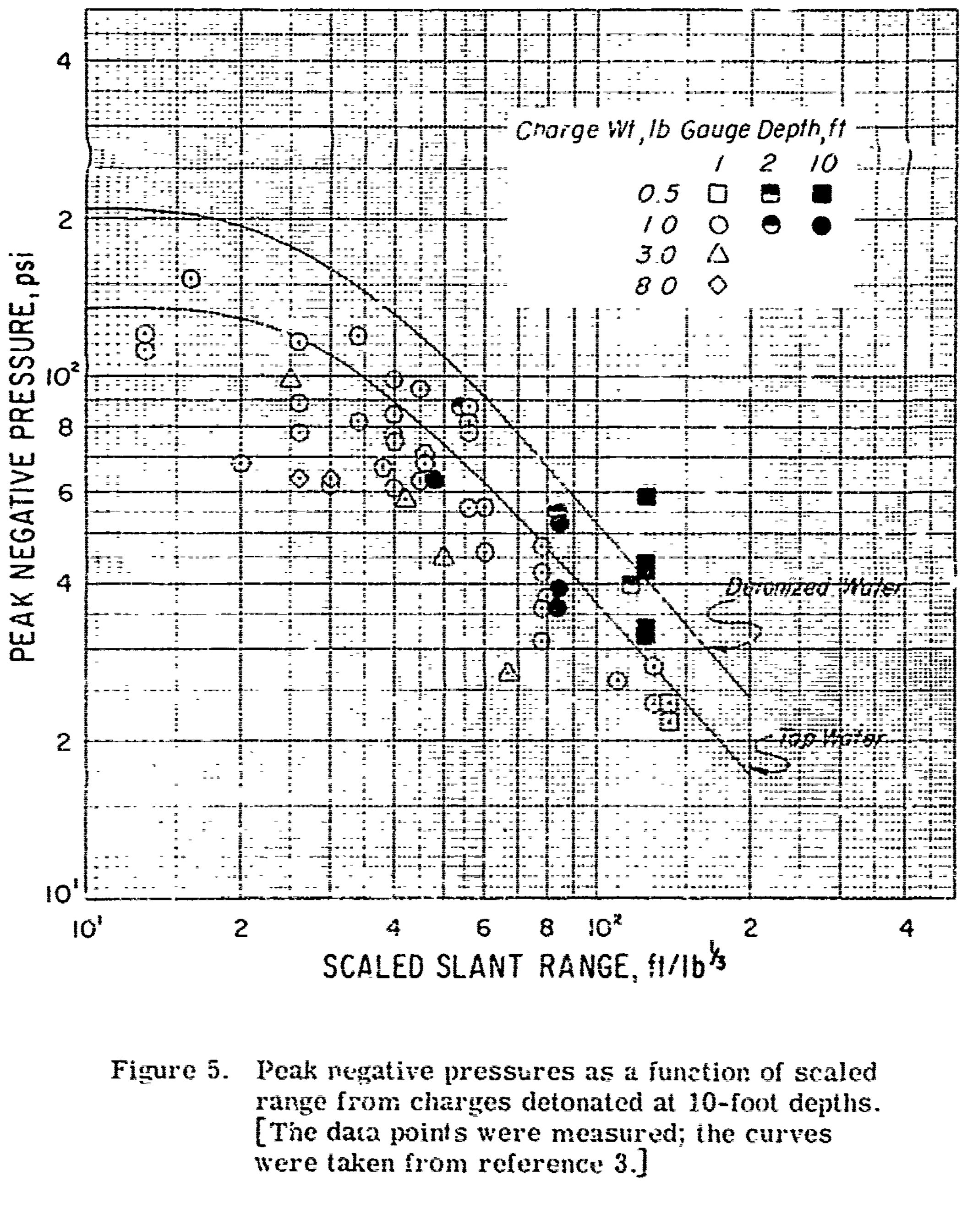


Figure 5. Peak negative pressures as a function of scaled range from charges detonated at 10-foot depths. [The data points were measured; the curves were taken from reference 3.]

for tap water from reference 3. The curves were obtained by measuring with piezoelectric gauges the tension in the reflected wave in a vertical pipe filled with water. The bottom of the pipe contained a piston that was driven by a lead bullet fired at its center. The upper end of the pipe was open. The results showed that the greater the pressure in the incident wave, the greater was the tension in the reflected wave, with maximum values in the tension wave leveling off at 8.5 atmospheres for tap water and 15 atmospheres for boiled deionized water.

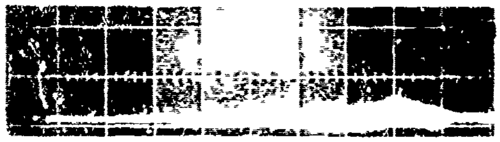
Bottom Reflections

A limited number of measurements were made of the waves that reflected from the bottom of the pond. The waveforms of these bottom reflections, recorded by gauges at 1-foot depths on 1-pound Pentolite charge firings, are illustrated in Figure 6. As seen in the figure, the reflected waves recorded over the 13- and 45-foot ranges were altered markedly from the ideal form that could be expected. The peak pressures were not on the leading portion of the waves. At and beyond the 60-foot range, the reflected waves appeared more normal in their pattern. Figure 7 gives the measured peak pressures and impulses in the bottom reflections along with the calculated curves. The peak pressure in the bottom reflected waves can be seen to be well below the calculated curves within the 45-foot range. Beyond 45 feet they were more near the curves. Measured impulses were an order of magnitude below the theoretical curve.

In contrast to peak pressure and impulse, the time between the incident and reflected shock waves and the cut-off times for the reflected wave were in fair agreement with the calculated curves, Figure 8. The time between shocks ranged from near 10 msec at the closest range, down to 1.0 to 1.5 msec at the 130-foot range.

General Procedures in Tests Run With Mammals

One hundred and one Columbia-Rambouillet female sheep, 37 Dalmation dogs, and six rhesus monkeys were utilized on these tests. In addition, nine sheep and one dog were used as control animals to check out the effects, if any, which were due to handling of the animals, tethering them beneath the grid, and lowering them beneath the surface while connected to the life-support system.



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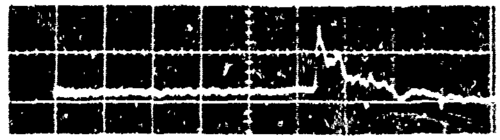

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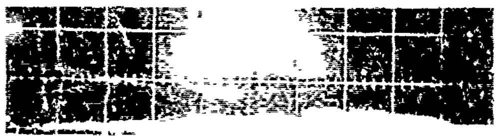

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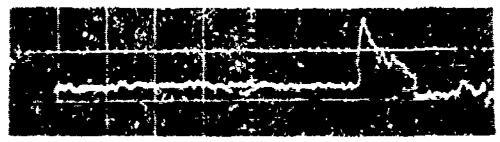
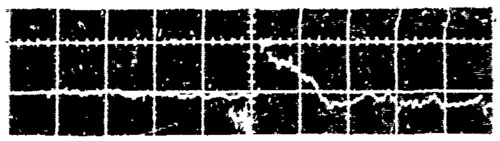
Slant Range: [illegible] ft Horiz.: 2.0 msec/div



Shot No.: [illegible] Scale:
Gauge No.: 3264 Vertical: 62 psi/div
Slant Range: [illegible] ft Horiz.: 0.1 msec/div

Shot No.: 194 Scale:
Gauge No.: [illegible] Vertical: 243 psi/div
Slant Range: 20 ft Horiz.: 2.0 msec/div



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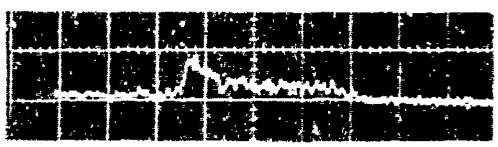

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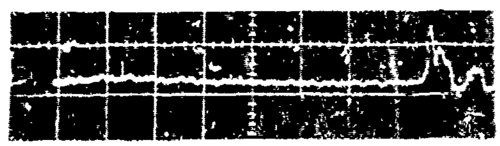

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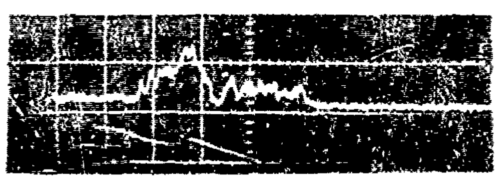
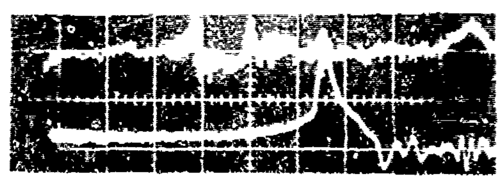


Shot No.: 200 Scale:
Gauge No.: 3264 Vertical: 109 psi/div
Slant Range: 45 ft Horiz.: 0.1 msec/div



Shot No.: [illegible] Scale:
Gauge No.: 3264 Vertical: 43 psi/div
Slant Range: 130 ft Horiz.: 0.05 msec/div

Figure 6. Oscillograms of bottom reflected waves recorded by gauges at 1-foot depths when 1-pound charges were detonated at 10-foot depths.

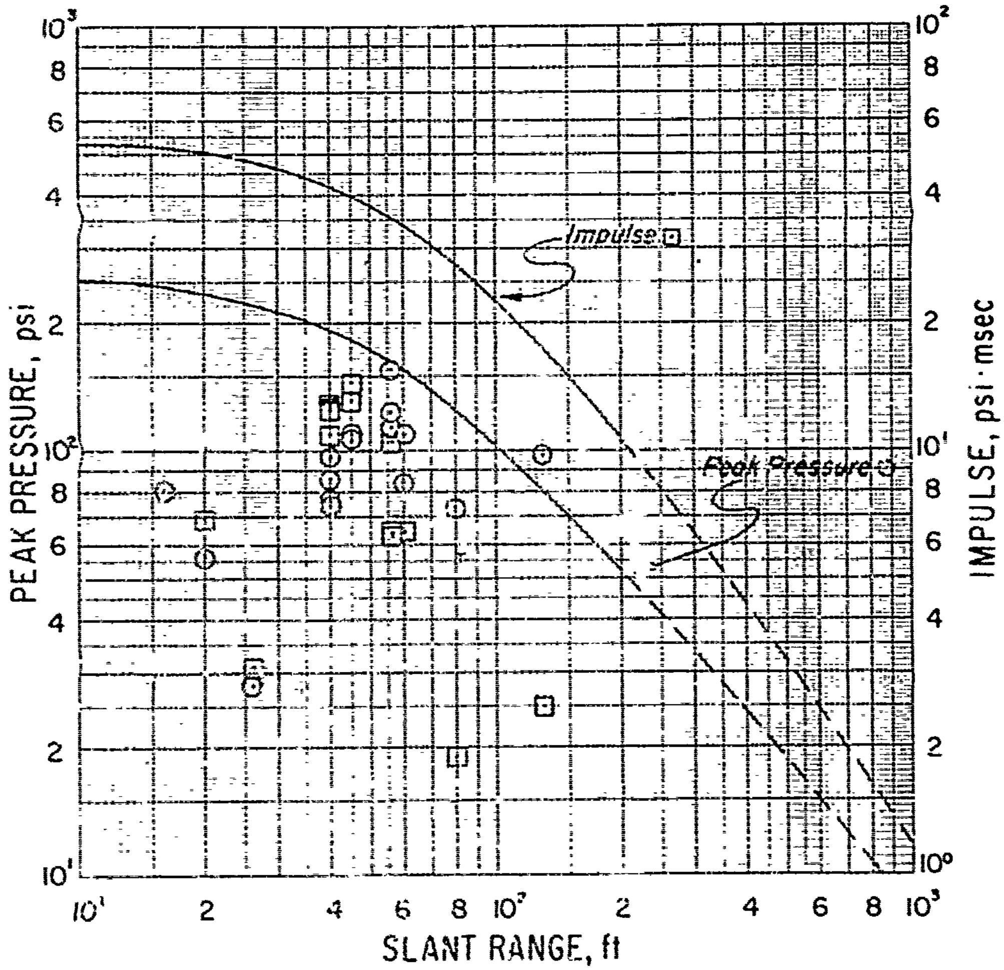


Figure 7. Peak pressure and impulse in bottom reflected waves at 1-foot depths as a function of range from 1-pound charges detonated at 10-foot depths. [The data points were measured; the curves were computed.]

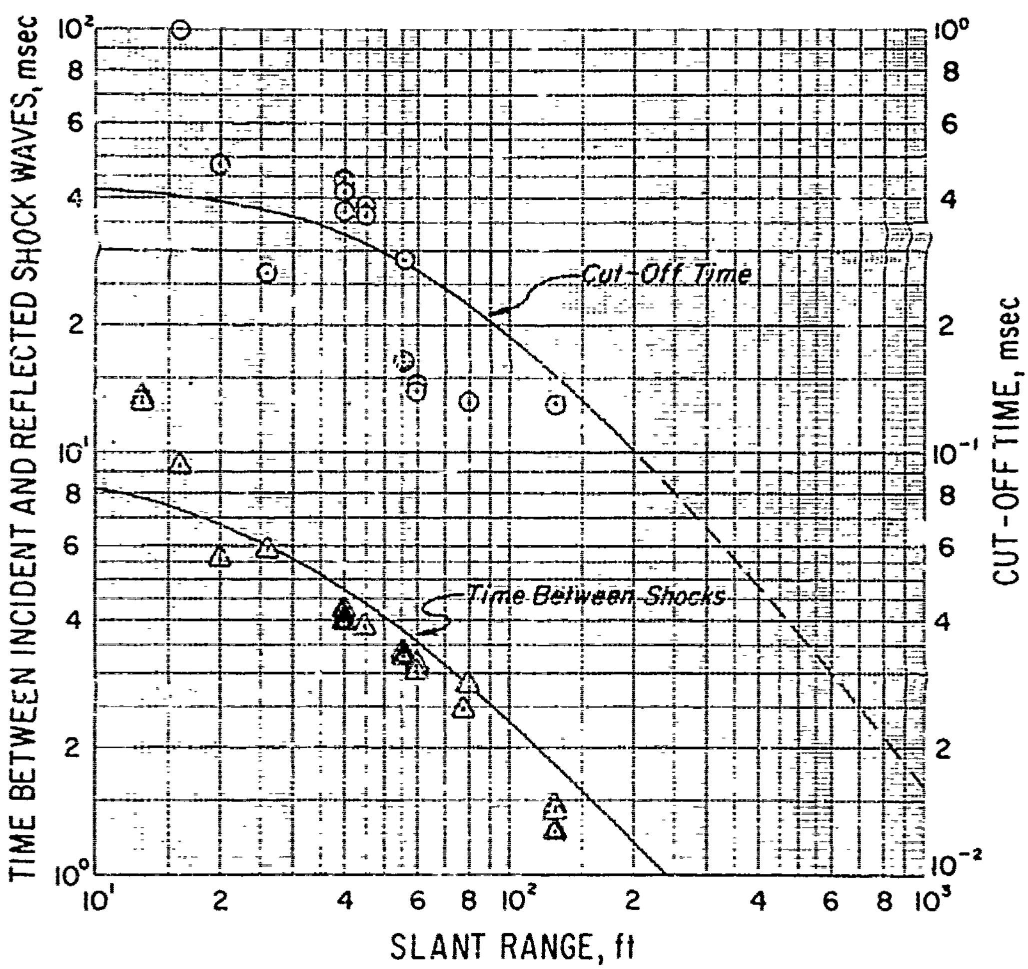


Figure 8. Cut-off time for bottom reflected waves and time between the incident and reflected shock waves at 1-foot depths as a function of range from 1-pound charges detonated at 10-foot depths. [The data points were measured; the curves were computed.]

In general, three animals were exposed per test. With few exceptions, they were all at the same range on a given shot. Most of the tests were run with subjects mounted vertically in the water, long axis perpendicular to the surface as shown in Figure 9. The depth at which sheep and dogs were placed was measured from the water surface to their xiphisternum. Monkeys were submerged to about their neck (glottis) level, shoulders beneath the surface, and were designated as 1-foot depths. Due to their smaller size, their xiphisternum was not 1-foot deep. All animals were right-side-on to the charge, including those tested horizontal to the surface. The depth of the horizontal animals (0.5 or 1 foot) was measured from the water surface to the ventral or dorsal surface of their trunks for prone or supine orientations, respectively.

All the test subjects were autopsied 2 hours following the test. At postmortem, the entire length of the G.I. tract was examined carefully. It was slit open, its contents washed out, and the condition of the mucosal lining in the contused areas was recorded. Table 1 summarizes the three series of experiments run with mammals.

Animals Perpendicular to the Surface

The main series of experiments involved 43 tests with 0.5-, 1-, 3-, and 8-pound charges. Most of them were run with animals at 1-foot depths and at increasing distances from the 1-pound charges. Based on the initial results from the 1-pound charge firings, tentative biological endpoints (a given severity of injury) and corresponding impulse levels were chosen. These then were confirmed with dogs and monkeys on the surface and with sheep beneath the surface. The endpoints were: threshold for lung injury (about 40 psi·msec), threshold for G.I. tract contusions (near 20 psi·msec), and a no-effect level (approximately 10 psi·msec or less).

The 30-*foot-deep* portion of the pond was too small to confirm a no-effect range from 3- and 8-pound charges with animals at 1-foot depths. With 1-pound charges, it was necessary to work at ranges beyond 100 feet in order to obtain a certain no-effect range. A rigging was placed across the east end of the pond so that animals could be exposed at the 130-foot range. The charge was 60 feet from the west end of the pond, and the targets were in water 15 feet deep.

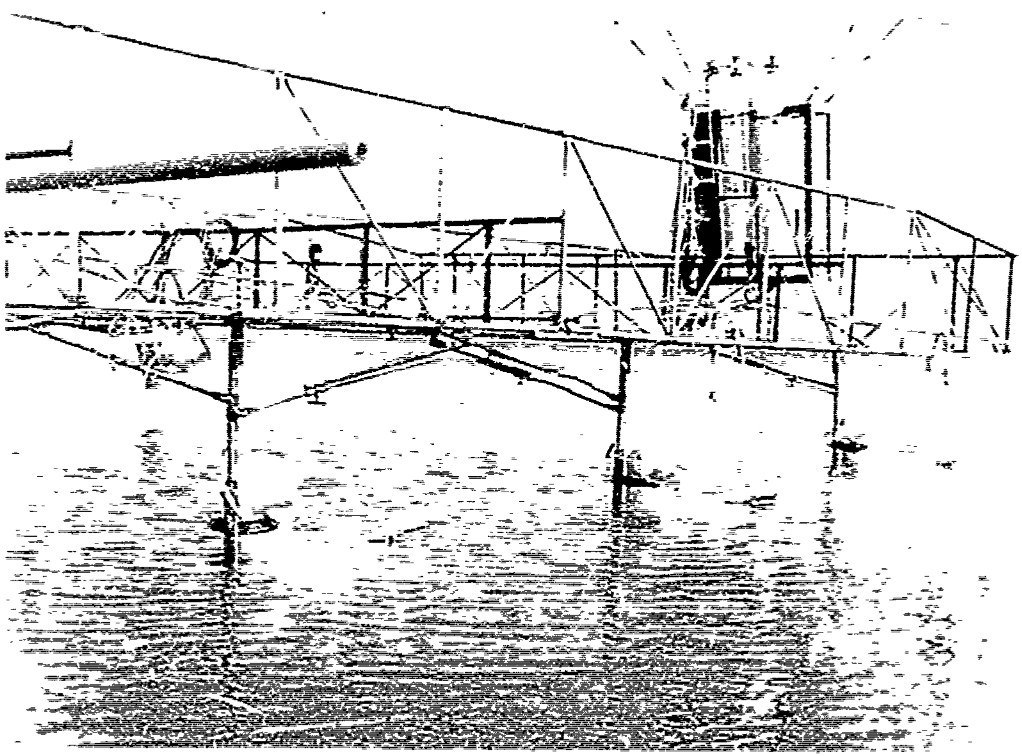


Figure 9. Sheep at 1-foot depths.

TABLE 1. SUMMARY OF THE EXPERIMENTS RUN WITH MAMMALS

Charge Weight, lb	Number of Charges Detonated	Depth of Animals, ft	Number of Animals	Slant Range, ft	Objectives
0.5	7	1, 2, 10	21 Sheep 3 Dogs	93 100 [illegible]0	To determine the effects of low-level impulses of 10 psi·msec and less.
1.0	30	1, 2, 10	57 Sheep 21 Dogs 6 Monkeys	26 to 130	To determine how the nature and incidence of blast injuries fall off with range and establish a no-effect range—impulses from 40 to 2 psi·msec.
3.0	4	1	16 Sheep	36 to 97	To assess the effects of impulse levels of 40, 20, 10, and 6 psi·msec from 3-lb charges.
8.0	2	1	12 Sheep	52 and 60	To assess the effects of impulses of 40 and 20 psi·msec from 8-lb charges.
1.0	4	0.5 & 1.0	11 Sheep 1 Dog	13 and 26	To compare lung and G.I. tract damage in animals horizontal to surface[a] and at the same depth.
1.0	8	2	24 Dogs	20 to 60	To determine response of dog eardrums to underwater blasts.

[a] All the other animals were oriented vertically in the water.

The life-support system which supplied air to the sheep at 2- and 10-foot depths consisted of a face mask (made from polyethylene bottles) having an air inlet hose in the side and a one-way outlet valve in the front of the mask. It covered the animal's nose and mouth and was held in place by four strings tied to the back of the head. The compressed air was delivered to the mask via plastic tubing connected to a manifold of five pressure regulators fastened to two air bottles in series. When animals were exposed at 10-foot depths, 2 psi was applied to the system once the mask was attached to the animal. The pressure was then increased to 6 psi and the rigging lowered to place the animals at the 10-foot depth. Following the detonation, the animals were returned to the surface within 1 minute, the delivery pressure was reduced to 2 psi, and the face masks were removed quickly and inspected for water.

Animals Horizontal to the Surface

A series of four tests was run with the animals horizontal to the surface, Table 1. On two of the tests, five animals were at 0.5-foot depths in the prone and supine positions and one was in the upright orientation at a 1-foot depth. On the two tests with animals at 1-foot depths, they were all prone. The depths were measured from the water surface to the undersurface of their trunks.

Eardrum Response Tests

Eight tests were run specifically for eardrum response data, Table 1. Dogs were used because the size and geometry of their eardrum and middle ear approximate man's more so than other animals. The 24 dogs were oriented vertically in the water with their ears exactly at a 1-foot depth. They were right-side-on to the charge with their right ear facing the charge. In order to maintain the exact position of the head, freshly sacrificed animals were used. After sacrifice, the pinna of the ear was clipped to approximate the size of the human's. Twelve of the 24 dogs used in this series had been exposed previously to blasts at 1-foot depths, head above the surface, in the first series of tests mentioned. To evaluate the extent of ear injury, the middle ear was dissected open from the brain side of the skull, then photographed.

Birds

Eighty-one Mallard ducks with a mean body weight of 1.16 (0.89-1.49) kg and nine Rouen ducks with a mean body weight of 2.33 (1.92-2.84) kg were used in this study. Eight Mallards and two Rouens served as controls to check out the effects of handling and placing them beneath the surface for 25 seconds.

There were two or three birds on each shot. They always were oriented right-side-on to the charge. The distance from the ventral surface of the ducks to the surface of the water was taken as their immersion depth. The majority of the birds were mounted in holding devices, as shown in Figure 1C, which consisted of 14- by 24-inch frames constructed from 3/8-inch steel rods. The birds were placed in harnesses made of 2-inch mesh nylon and suspended in the frames by 1/8-inch nylon cords.

Table 2 summarizes the three series of experiments run with birds. In the first series, 48 Mallard ducks at 2-foot depths were placed at seven ranges within the lethal zone. The purpose was to correlate mortality with impulse and ascertain the nature of the lethal immersion-blast injuries. Those which survived were observed for 14 days to find out if birds with serious underwater-blast injuries followed the same pattern as mammals surviving air blasts; namely, few, if any, delayed deaths and a relatively rapid recovery time of 1 to 2 weeks.

The second series of tests involved testing 27 Mallard ducks at 2-foot depths, at four ranges beyond the lethal zone, to establish threshold injury and safe impulse levels for birds beneath the water surface. They were autopsied at 2 hours in order to evaluate very minor lesions that heal rapidly.

The third series consisted of subjecting nine Rouen and six Mallard ducks to underwater blasts while held on the surface at a depth of 0.25 foot (the measured draft of a floating duck). The ducks were tested at 12 ranges to determine lethal, injurious, and safe conditions for birds on the surface.

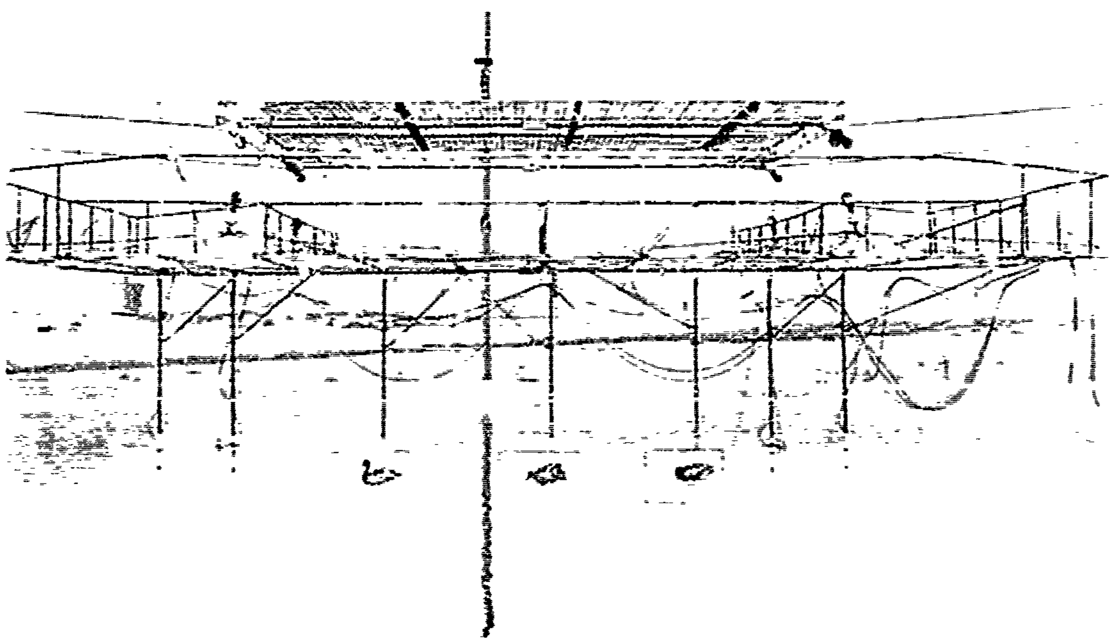


Figure 10. Duck test array.

TABLE 2. SUMMARY OF THE EXPERIMENTS RUN WITH BIRDS

Charge Weight, ft	Number of Charges Detonated	Depth of Birds, ft	Number of Birds	Slant Range, ft	Objectives
1.0	17	2.0	48 Mallards	7 Ranges - Between 23 and 36	To obtain dose-mortality curves; follow survivors 14 days for delayed deaths and recovery.
1.0	9	2.0	27 Mallards	4 Ranges - Between 36 and 110	To determine the extent of blast injuries beyond the lethal zone. Birds examined at 2 hr.
1.0	3	0.25	6 Rouens	6 Ranges - Between 9.8 and 17.9	To determine mortality and injuries at various ranges for birds on the surface. Survivors in the near field examined at 24 or 72 hr; those in the far field at 2 hr.
8.0	2	0.25	6 Mallards	4 Ranges - Between 15 and 21	
8.0	1	0.25	3 Rouens	13, 14, and 15	

RESULTS

Mammals

Nature and Severity of Underwater-Blast Injuries

In the main test series wherein animals were oriented vertically in the water, there were no deaths from blast injuries. The only animals which appeared hurt from external signs were the three sheep tested at a 1-foot depth and at a slant range of 26 feet from a 1-pound charge. They were docile and remained lying down after removal from their mounts but were on their feet at 5 minutes when the raft was docked. They did not run around the raft as the other sheep did when released from their mounts.

The immersion-blast injuries were, for the most part, confined to the lungs and G. I. tract. There were some eardrums ruptured in those animals tested beneath the surface but only at the shorter ranges. The injuries were similar to those repeatedly described in the literature for man and animals but of minor severity; i. e., there were no instances of either ruptured lungs or ruptured G. I. tracts. At the shorter ranges, animals sustained slight amounts of lung hemorrhages as illustrated in Figure 11 and multiple contusions of the G. I. tract, Figures 12 and 13. The contusions were small in area and scattered through the small intestine, caecum, large intestine, including the spiralis, ansa terminalis, and rectum. There was only one case of contusions in the stomach. Some of these contusions, even though small in area (1/2-inch or less), were of sufficient severity to ulcerate the mucosal layer of tissue that lines the lumen of these organs, Figure 13. These ulcerations would account for small blood clots found in the feces of many of the animals. In no instance did the blood clots in the feces amount to more than a few drops of blood. This lesion commonly would cause the animals to defecate soon after their removal from the water. In general, the number and size of these contused areas would decrease with the distance from the charge. The most far-field lesions were a

Figure 11. Slight lung hemorrhage from sheep at a 1 - foot depth, 52 feet from an 8-pound charge detonated at a 10-foot depth. [The peak pressure was 493 psi; the impulse was 36. 5 psi- msec.]

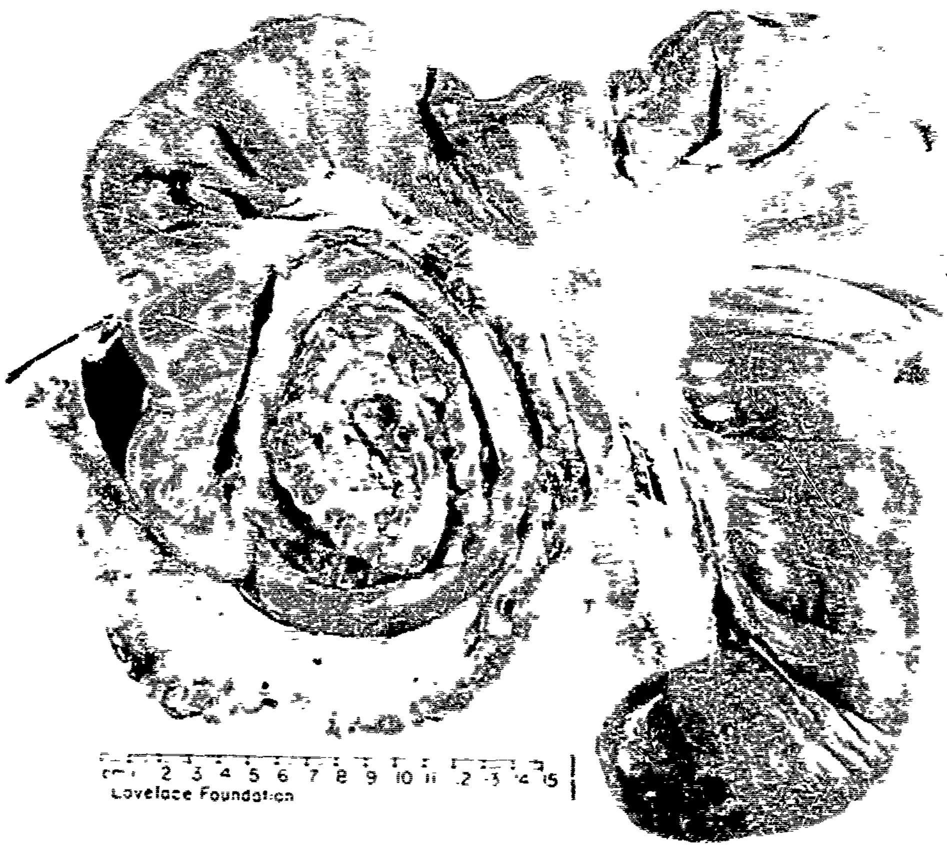


Figure 12. Lower portion of G.I. tract from Sheep No. 186, Shot No. 140. [Multiple contusions of spiralis, ansa terminalis, and rectum (lower left). Target at a 1-foot depth. 52 feet from an 8-pound charge detonated at a 10-foot depth.]

Figure 13. Lower portion of G.I. tract from Sheep No. 161, Shot No. 140. [Large colon opened to show ulceration of mucosal lining (upper hemostat). Target at a 1-foot depth. 52 feet from an 8-pound charge detonated at a 10-foot depth. The peak pressure was 493 psi; the impulse was 36.5 psi·msec.]

few petechia or small hyperemic spots on the lower portion of the rectum near the anus. A more severe form of scattered multiple petechia lining the rectum is illustrated in Figure 14. The contusions of the G.I. tract were termed as contusions if ulcerations of the mucosal lining were associated with any of them and were termed as mild contusions if there were no ulcerations of the mucosal lining.

Underwater-Blast Injuries in Relation to Distance From 1-Pound Charges at 1-Foot Depths

Lung Hemorrhage

The incidence of lung hemorrhage in animals tested at 1-foot depths, in relation to slant ranges from 1-pound charges, appears in Figure 15. At the 26-foot slant range, slight lung hemorrhages occurred in the dog and monkey, and petechial hemorrhages were found in the lungs of one of the three sheep. There were no lung lesions detected in animals at ranges beyond 26 feet.

Gastrointestinal Lesions

The general pattern of G. I. tract damage in animals at 1-foot depths, in relation to slant ranges from 1-pound charges, is given in Figure 15. The general step-down pattern of severity of G.I. tract lesions with range can be seen in Figure 15. Contusions of the more severe form extended out to 35 to 40 feet. Beyond the 60-foot range, the lesion found was a 1-inch-diameter mild contusion in the caecum of a sheep at the 78-foot range. All 12 sheep tested at the 130-foot range were negative.

That the G.I. tract lesions extended to greater ranges than did the lung lesions was because animals upright in the water received almost twice the impulse at the lower portions of their bodies than at the upper portions nearer the surface. For instance, sheep at the 56-foot range from a 1-pound detonation received 7 psi msec at their lungs, 0.5 feet from the surface, while much of the G.I. tract at a 1.5-foot depth received 16 psi·msec.

Underwater-Blast Injuries as a Function of Impulse

The incidence of lung hemorrhages and G. I. tract lesions, along with the associated impulse values for all the animals exposed to the underwater blast in a vertical position, appears in Figure 16. The impulse values corresponding to each animal data point were those measured at the animal's designated depth: 1,

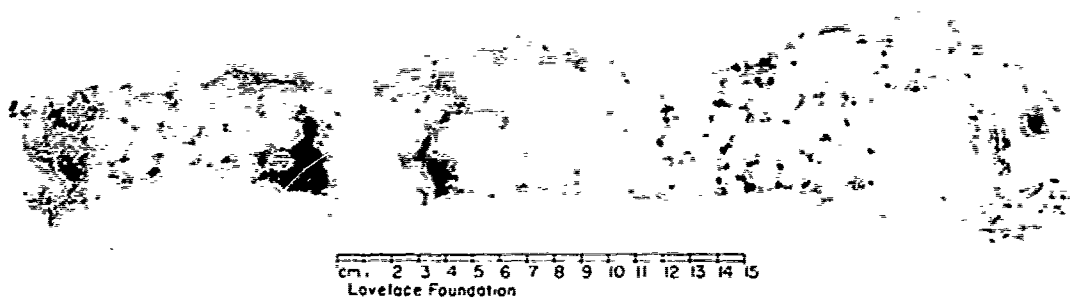
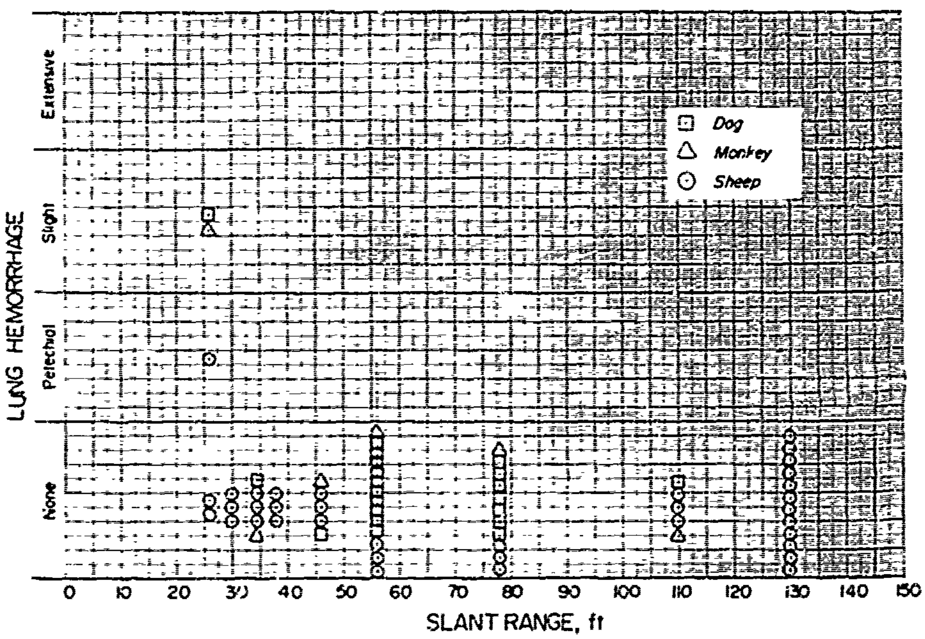


Figure 14. The rectum of sheep opened to show scattered petechiation and contusion. [The only other lesion was a 1/8-inch-diameter contusion in caecum. Target at a 1-foot depth, 38 feet from a 1-pound charge detonated at a 10-foot depth. The peak pressure was 400 psi; the impulse was 25.8 psi·msec.]



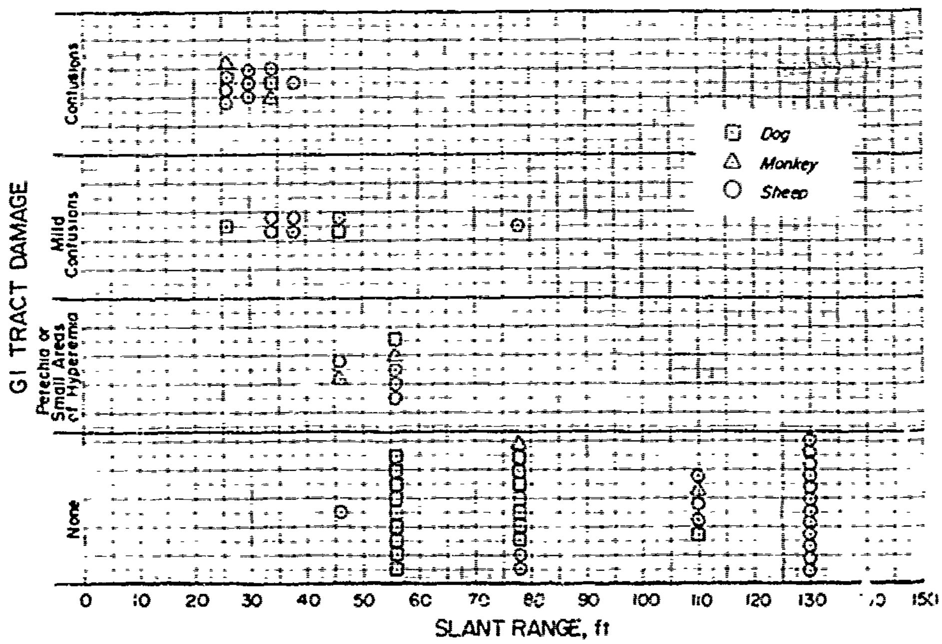


Figure 15. The incidence of lung hemorrhage and G.I. tract injuries in animals at 1-foot depths in relation to slant range from 1-pound charges.

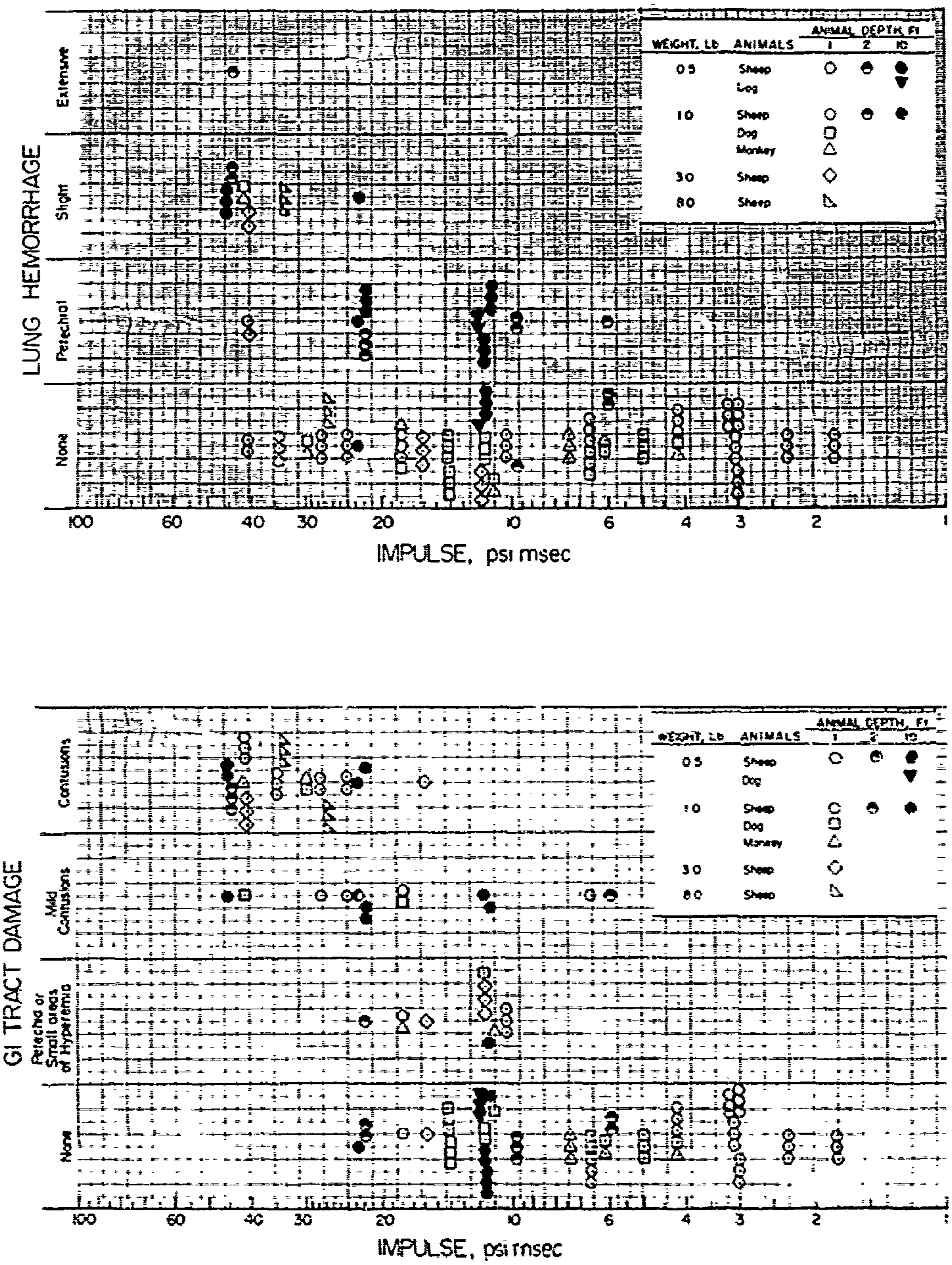


Figure 16. The incidence of lung hemorrhage and G. I. tract injuries as a function of impulse, psi· msec.

2, or 10 feet. As already mentioned, all these animals survived the underwater blast.

As seen in Figure 16, there was about a 50 percent incidence of slight lung hemorrhages at an impulse of 34 psi·msec. At an impulse on the order of 20 to 25 psi·msec, about half the animals sustained petechial lung hemorrhages. Below 20 psi·msec, there were no instances of slight lung hemorrhages. At impulses of 8 psi·msec and less, there was only one instance of petechial lung hemorrhage recorded in a sheep at 5.6 psi·msec. It is interesting to note that at the higher impulse levels some of the animals sustained no lung injury whatsoever. As already mentioned, the lung lesions extended to lower impulse levels in those animals exposed beneath the surface than those at 1-foot depths. More about that later.

According to Figure 16, there was about a 50 percent incidence of G.I. tract contusions at impulse levels of 25 to 27 psi·msec. There were no contusions with ulcerations of the mucosal lining below an impulse level of about 15 psi msec. About one half of the animals subjected to an impulse of 21 to 23 psi·msec had either contusions or mild contusions in their G.I. tracts. The only lesions encountered below 10 psi·msec were two cases of animals with mild contusions at 6 to 7 psi·msec. The immersion-blast injuries in each of the animals, along with the underwater-blast wave parameters measured adjacent to them, were listed in reference 4.

Animals Horizontal to Surface

Table 3 compares the severity of lung injury to that for the G.I. tract in six animals placed horizontal to the surface at 1-foot depths. The rationale was to expose the thorax and the abdomen of the animal as nearly as possible to the same depth and to the same impulse. Any air- or gas-containing organ, then, might be damaged to the same extent. The animals at the 26-foot range sustained slight lung hemorrhages and a few mild contusions of the G.I. tract. Those at the 16-foot range sustained slight to extensive lung hemorrhages and mild to multiple contusions with ulcerations into the lumen of the G.I. tract.

TABLE 3. EFFECTS OF 1-POUND CHARGES FIRED AT 10-FOOT DEPTHS ON MAMMALS AT 1-FOOT DEPTHS HORIZONTAL TO SURFACE

Shot No.	Slant Range, ft (Horizontal Range, ft)	Pressure, psi (Impulse, psi·msec) [Duration, msec]	Animal No. (Body Wt., kg)	Effects
189	16 (13.2)	987[a] (99.6) [0.281]	S-62 (43)	Extensive lung hemorrhage, (lung weight, 2.38%). Bloody froth at nares. Scattered light contusions with slight ulcerations of mucosa; feces, no blood clots. Hemorrhage in tracheal wall.
			S-61 (46)	Slight lung hemorrhage, (lung weight, 0.87%). Sub-serosal extravasation in the caecum; no feces. Extensive hemorrhage in trachal wall.
			S-63 (45)	Extensive lung hemorrhage, (lung weight, 1.34%). Bloody froth at nares. Multiple contusions with ulcerations of G. I. tract; no feces. Hemorrhage in tracheal wall.
183	26 (24)	588[a] (50.6) [0.173]	S-141 (36)	Respiration normal. Petechial lung hemorrhage, (lung weight, 0.95%). A few small (1/8-1/4-in.) hyperemic areas in the ansa terminalis. No feces.
			S-154 (34)	Respiration normal. Slight lung hemorrhage, (lung weight, 1.08%). Several mild contusions in the ansa terminalis. No feces.
			D-231 (16)	Respiration normal. Slight lung hemorrhage (lung weight, 0.91%). One small (1/8-in.) mild contusion in rectum. No feces.

[a] Pressure-time measured at 1-ft depths.

All animals were oriented prone in the water.

As far as one can go in comparing the severity of damage between two different organ systems, the results indicate that the extent of damage was about the same. Possibly, the lungs were more damaged than the G.I. tract.

Table 4 gives the results obtained with horizontal subjects at 0.5-foot depths in the prone and supine positions along with one animal that was vertical in the water at the usual 1-foot depth. The vertical animals received extensive lung hemorrhage and multiple ruptures of the small intestine. The animals at 0.5-foot depths did not receive any G.I. tract ruptures, and extent of lung hemorrhage was less than that found in the upright animal. There was not a remarkable difference in the extent of injuries in the supine compared to the prone animals. The lung weights of the supine sheep (1.45 and 1.49 percent of their body weight) were slightly higher than those from the prone ones (1.23 and 1.27 percent).

Ear Injury in Dogs

Table 5 gives the eardrum rupture data for dogs in terms of the percent of area of the tympanum destroyed and the corresponding range and pressure-time parameters. Photographs illustrating the different severities of ear injury are shown in Figure 17. In general, the eardrums on the right side of the head (the heads were right-side-on) were more damaged than the left ones. The right ears from animals at the 20-foot range were more damaged than those at the 40-foot range in terms of the area of the tympanum destroyed and ossicles damaged. In three cases, eardrum rupture was bilateral; in the other cases, it was unilateral.

Figure 18 gives the results of probit analysis that was run relating right eardrum rupture as a function of the log impulse. The data for animals at the 40-foot range were divided into two groups. The results indicate a 50 percent incidence of right eardrum rupture at an impulse of 22.6 psi·msec. The 85 percent confidence limits were 21.7 to 25.2 psi·msec. For both right and left ears, there was a 36 percent incidence of eardrum rupture in dogs at the 40-foot range. The mean impulse measured at that distance was 22.0 psi·msec; the mean peak pressure was 320 psi.

TABLE 4. EFFECTS OF 1-POUND CHARGES FIRED AT 10-FOOT DEPTHS ON TARGETS AT 0.5-FOOT DEPTHS

Shot No.	Slant Range, ft (Horizontal Range, ft)	Pressure, psi (Impulse, psi·msec) [Duration, msec]	Animal No. (Body Wt., kg)	Effects
187	13 (10)	1147[a] (132.6) [0.354] 105[illegible][b] (55.7) [0.157]	S-55 (43) VRSO[c]	Extensive lung hemorrhage, (lung weight, 1.60%). Down; grunting respiration. Six ruptures of small intestine. Multiple large areas of submucosal contusions with ulcerations of mucosal lining throughout stomach, large and small intestine, and rectum. Frank blood from anus.
			S-56 (49) Prone[c]	Slight lung hemorrhage (lung weight, 1.27%). Four one-inch segments of submucosal mild contusions in ansa terminalis and rectum. Feces: no hemorrhage.
			S-57 (43) Supine[c]	Extensive lung hemorrhage, (lung weight, 1.45%). Few half inch subserosal contusions and hyperemic areas in ansa terminalis. No ulcerations of mucosal lining. No feces
188	13 (10)	1224[a] (135.4) [0.358] 1089[b] (85.7) [0.157]	S-58 ([illegible]) Supine[c]	Extensive lung hemorrhage, (lung weight, 1.49%). Two submucosal contusions with ulceration of mucosal lining and one small mild contusion in caecum. Petechia surrounding fecal pellets in ansa spiralis. Feces no blood clots.

(continued)

TABLE 4. (Continued)

Shot No.	Slant Range, ft (Horizontal Range, ft)	Pressure, psi (Impulse, psi·msec) [Duration, msec]	Animal No. (Body Wt., kg)	Effects
188 (continued)			S-59[c] (50) Prone[c]	Extensive lung hemorrhage, (lung weight, 1.27%). Slight amount of bloody froth from nares. Small contusion on stomach, four 1/8-1/4-inch submucosal contusions on small intestine and scattered small areas of submucosal contusions throughout spiralis and ansa terminalis with pin-head size clots of blood in lumen.
			S-60 (49) Prone[c]	Extensive lung hemorrhage, (lung weight, 1.23%). Respiration slightly labored: slight amount of bloody froth from nares. Multiple small areas of subserosal contusions in small intestine. A 2-inch submucosal contusion in large colon and a few 1-inch submucosal contusions in ansa terminalis. No feces.

[a] Pressure-time measured at 1-ft depths.

[b] Pressure-time calculated for 0.5-ft depths.

[c] Animal Orientations: VRSO = Animal mounted vertically in the water right-side-on (long axis perpendicular to surface). Supine = Animal mounted horizontally in the water, supine. Prone = Animal mounted horizontally in the water, prone.

TABLE 5. EAR INJURY IN DOGS EXPOSED RIGHT-SIDE-ON WITH THEIR EARS AT 1-FOOT DEPTHS TO UNDERWATER BLASTS FROM 1-POUND TNT CHARGES DETONATED AT 10-FOOT DEPTHS

Shot No.	Slant Range, ft	Peak Pressure, psi (Impulse, psi·msec) [Cut-Off Time, msec]	Dog No.	Eardrum Rupture, Percent Destroyed				
				Right		Left		Totals
				Ruptured	Intact	Ruptured	Intact	
194	25	676[a]	204	40% b			-	
		(68.2)	217	80% b			-	4/6
		[0.214]	215	100% b		60%	-	(66.7%)
195	40	319	1		N/A[c]		-	
		(23.5)	217'	60%			-	3/5
		[0.113]	218	60%		40%		
204	40	327	200	90% b		5%		
		(22.7)	116		-	50%		3/5
		[0.108]	210		-		N/A	
208	40	328	261		-		-	
		(21.5)	102		-		-	1/6
		[0.103]	262		-	30%		
210	40	307	263		-		-	
		(20.4)	117	30%			-	1/6
		[0.105]	163'		-		-	
								8/22 (36.4%)
200	45	292	120		-		-	
		(19.2)	253		-		-	0/6
		[0.099]	200'		-		-	
206	45	293	220		-		-	
		(19.0)	100		-	20%		1/5
		[0.092]	208		-		N/A	
								1/11 (9.1%)
197	60	215	205		-		-	
		(12.4)	163		-		-	0/6
		[0.078]	202		-		-	

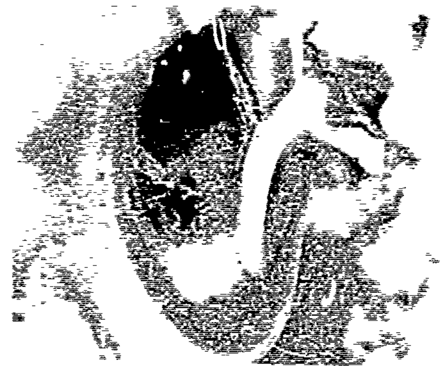
[a] Pressure time was measured at 1-ft depths.

[b] Ossicles fractured or disrupted; otherwise intact.

[c] Not assessible.

\- Indicates eardrum intact.

Dog No. 205, Right Ear



Dog No. 253, Left Ear

Dog No. 218, Right Ear

Dog No. 218, Left Ear

Dog No. 215, Right Ear

Dog No. 215, Left Ear

Figure 17. Dog eardrum and ossicular damage viewed from the middle ear.

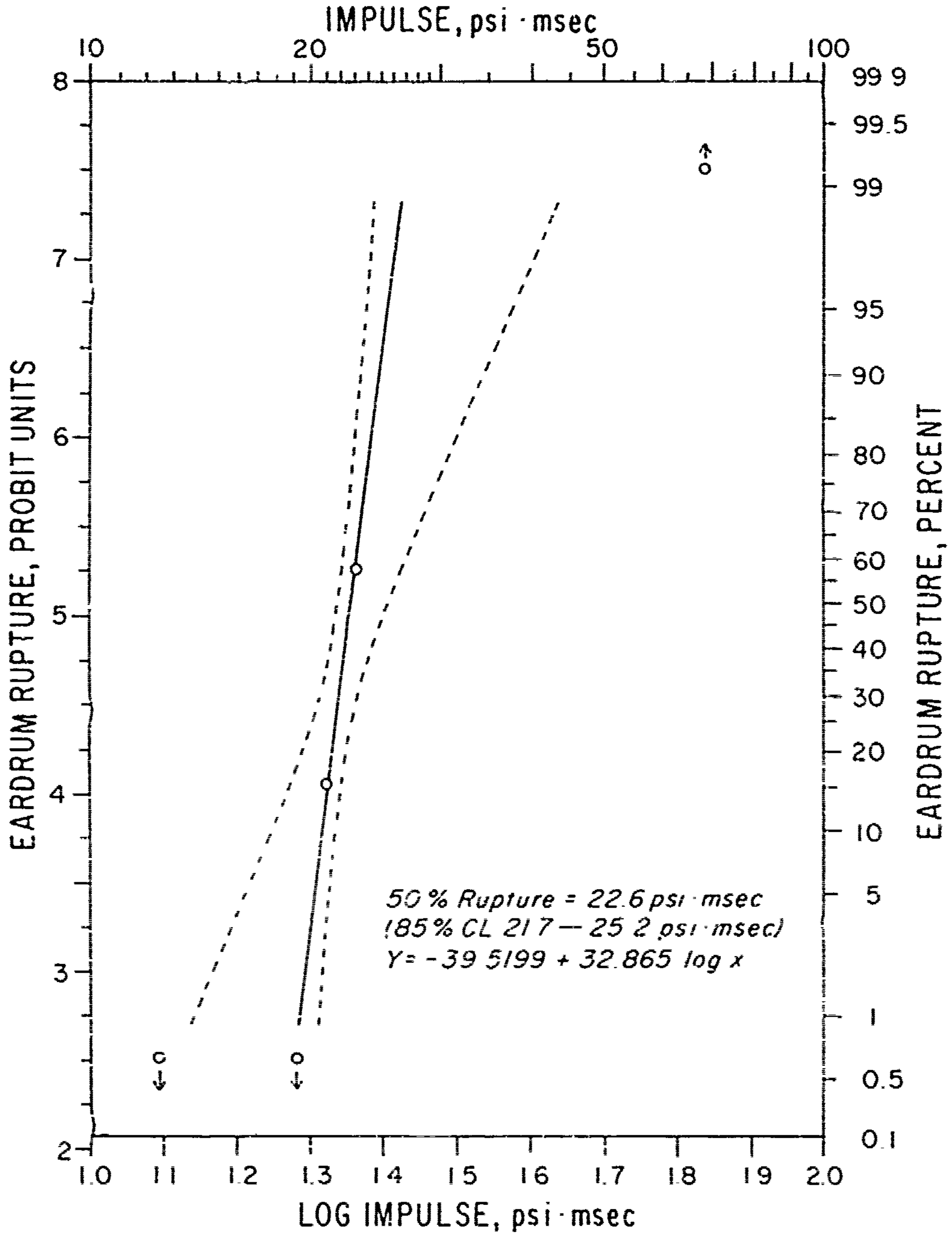


Figure 18. Probit dose-response curve for the right eardrums of dogs. [Arrows indicate 0 or 100-percent incidence of eardrum rupture.]

Control Animals

It was found that the life-support system could, in some instances, produce lung lesions and slight hemorrhages in the lining of the middle ears and frontal sinuses. In addition, contusions of the endocardium were found in these subjects that received no blast. One of the animals placed at a 10-foot depth exhibited petechia about the anal sphincter. This lesion could be a result of placing the animal in a seated position. Hyperemic spots in the lining of the G.I. tract have been found in control sheep from other experiments in this facility. Histological examination revealed them to be caused by parasitic round worms. In some of the experimental sheep in the present study, hyperemic areas were assessed histologically and found to be associated with these parasitic round worms.

Birds

Mortality

Table 6 presents the mortality data for the ducks tested at 2-foot depths at ranges between 23 and 36 feet. The nine ducks at and within the 28-foot range were killed by the blast. Some survived at 31 and 33 feet. There were no deaths at the 36-foot range.

A probit analysis was run on the data relating mortality in probit units to the log impulse measured at 2-foot depths. Figure 19 gives the probit mortality curve with its 95 percent confidence limits. The equation for the probit curve was:

$$y = -37.516 + 25.767 \log_{10} x \tag{6}$$

where y is the percent mortality in probit units, x is the impulse in psi msec, and -37.516 and 25.767 are the intercept and slope constants, respectively. The impulse associated with the 95 percent confidence limits for 1 percent mortality (LD_1) was 36.3 (28.0 to 39.1) psi·msec. The LD_{50} was about 10 psi·msec higher, 44.7 (42.8 to 47.8) psi·msec.

Table 7 presents the mortality data for Rouen and Mallard ducks exposed on the water surface. Death occurred at slant ranges of 13 and 14 feet from the

TABLE 6. MORTALITY FOR DUCKS AT 2-FOOT DEPTHS

Slant Range, ft	Peak Pressure, psi (Impulse, psi·msec) [Cut-Off Time, msec]	Mortality	
		r/n[a]	Percent
23	558 (70.9) [0.361]	3/3	100
27	455 (55.3) [0.314]	3/3	100
28	441 (51.7) [0.293]	3/3	100
31	402 (46.1) [0.277]	6/9	67
31–32	396 (43.3) [0.261]	3/12	25
33	363 (39.9) [0.252]	2/12	17
36	333 (35.6) [0.236]	0/6	0

[a] r/n = the number killed over the number tested.

All charges were 1 lb.

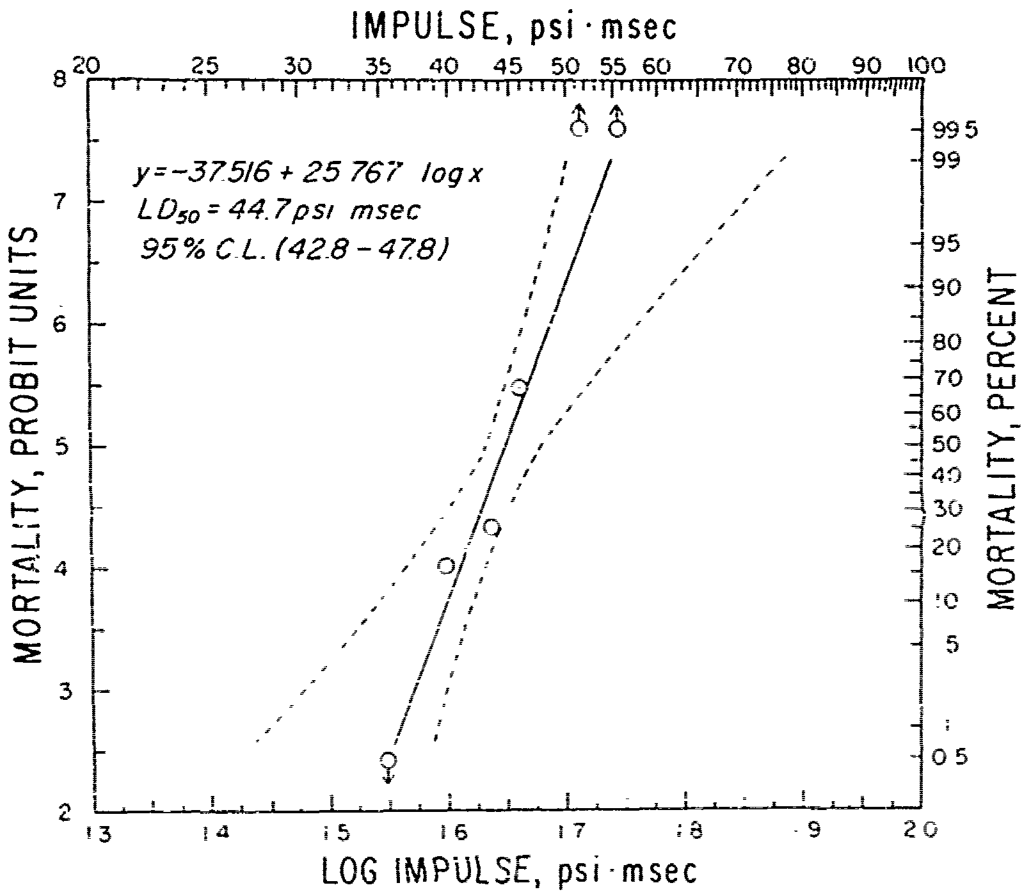


Figure 19. Probit mortality curve for Mallard ducks tested at 2-foot depths. [Arrows indicate 0 or 100 percent mortality.]

TABLE 7. MORTALITY AND INJURIES FOR DUCKS ON THE WATER SURFACE

Charge Weight, lb	Range, ft Slant/Horizontal	Peak Pressure, psi	Impulse, psi·msec	Cut-Off Time, msec	Effect	Lung Hemorrhage	Air Sacs	Liver Rupture
8.0	1[illegible].0/8.6	2484	172	0.095	Death[a]	Extensive	Ruptured	Extensive
8.0	14.0/10.0	2007	148	0.093	Death[a]	Extensive	Ruptured	Extensive
8.0	13.0/8.6	2335	148	0.079	Survived	Slight	Intact	Extensive
8.0	14.0/10.0	2152	129	0.074	Death	Extensive	Ruptured	Extensive
8.0	15.0/11.4	1995	114	0.069	Survived	Extensive	Ruptured	Extensive
8.0	15.0/11.4	1753	100	0.073	Survived[a]	Extensive	Ruptured	Extensive
8.0	17.0/14.0	1813	95	0.064	Survived[a]	Slight	Ruptured	Slight
1.0	9.8/1.0	1495	94	0.105	Survived	Extensive	Ruptured	Extensive
1.0	10.0/2.3	1454	90	0.103	Survived	Extensive	Intact	Extensive
1.0	11.0/5.1	1309	77	0.094	Survived	Extensive	Intact	Slight
8.0	19.0/16.3	1383	77	0.067	Survived[a]	Slight	Intact	Slight
1.0	12.0/7.0	1189	67	0.086	Survived	Slight	Intact	Slight
1.0	14.8/11.2	931	46	0.069	Survived	Slight	Intact	Slight
8.0	21.0/18.6	1153	42	0.047	Survived[a]	None	Intact	Slight
1.0	17.9/15.0	762	34	0.058	Survived	None	Intact	None

[a] Mallard ducks, the others were Rouens.

Blast parameters measured at 0.25-ft depths.

8-pound charges but not at 15 to 21 feet. The impulses at 13 and 14 feet were on the order of 129, 148, and 173 psi·msec. That high impulse levels were necessary to kill ducks on the surface probably was due to the fact that the birds were partly out of the water. Since the lungs of the birds were located dorsally along the vertebrae, these target organs mostly were above the water line.

Time of Death

Birds killed by the blast had short survival times. Fourteen of the 20 fatalities tested at 2-foot depths expired within 3 minutes. Four died within 30 minutes and one died at 5 hours postshot.

External Signs of Injury

All the birds that died from the blast exhibited labored breathing, appeared comatose, and were unable to stand on their own. In regard to the survivors, all three in the 46.1 psi·msec group exhibited labored respiration. Two would not walk within 2 minutes, and one would not stand. All nine 43.3 psi·msec survivors also had labored respiration. Three of the nine were comatose and unable to stand or walk by 2 minutes. Six of the 10 birds from the 39.9 psi·msec group had labored respiration, three of which were not walking at 2 minutes postshot. Only one out of the six Mallards subjected to 35.6 psi·msec exhibited any external signs of injury, and this was in the form of a slightly labored respiration.

Ducks tested on the surface and subjected to impulse levels of 95 psi·msec and below did not show external signs of injury. Those given greater impulses did. Four of the subjects were let go with a light string attached to their legs to see if they would fly. Three of the ducks which received impulses of 95, 77, and 42 psi·msec could fly when released soon after the shot. The bird given 100 psi·msec would not fly.

Nature of Injuries

The types of injuries recorded in the 20 duck fatalities tested at 2-foot depths are listed in Table 8. All those that expired had extensive pulmonary hemorrhage, ruptured livers, and ruptured kidneys. Coronary air embolism was seen in seven of the birds. Over half the ducks had ruptured air sacs and ruptured eardrums.

TABLE 8. NATURE AND INCIDENCE OF INJURIES FOR 20 DUCK FATALITIES AT 2-FOOT DEPTHS

Injuries	Number With Lesions	Percent
Coronary Air Emboli	7	35
Extensive Lung Hemorrhage	20	100
Ruptured Air Sacs	13	65
Eardrum Rupture:		
Bilateral	11	55
Unilateral	5	25
None	4	20
Liver Rupture	20	100
Hemorrhagic Kidneys	20	100

Impulses ranged between 36 and 71 psi-msec.

All charges were 1 lb.

The pattern of injuries in the ducks that received blasts on the surface was similar to those at 2 feet except for the absence of kidney damage.

Blast Injuries Beyond the Lethal Zone

Table 9 lists the injuries in the Mallard ducks tested at 2-foot depths, at four ranges of from 36 to 110 feet from 1-pound charges. Only the birds at the 36-foot range, impulse of 35.2 psi·msec (LD_1 level), appeared hurt and had remarkable internal injuries. Most of them had extensive lung hemorrhage, and half of them had *liver* and kidney damage. Those birds exposed to blast at the 83- and 110-foot ranges (impulses of 9.2 and 5.7 psi msec) were uninjured--a small spot of hemorrhage was detected in the lungs of one bird at 83 feet. There were no eardrum ruptures in these birds. It was suspected, in planning these experiments, that eardrum rupture would be the most far-reaching effect among the underwater-blast injuries in birds, but this was not the case.

Remnants of Blast Injury in 14-Day Survivors

As already mentioned, 28 birds that survived blasts in the lethal zone were observed for 14 days and then examined. There were no delayed deaths, and at 14 days they *all* appeared normal. At autopsy, all the air sacs and ear-drums were intact. Most of the livers had small blood clots adhering to them. Most of their lungs showed scattered areas of hemosiderin and discoloration. One animal still had an unabsorbed blood clot along its kidney.

TABLE 9. INJURIES IN MALLARD DUCKS AT 2-FOOT DEPTHS BEYOND THE LETHAL ZONE

Slant Range, ft	Peak Pressure, psi (Impulse, psi · msec) [Cut-Off Time, msec]	Number of Birds	Lung Hemorrhage, (Percent Lung Weight)	Number of Birds With: Liver Ruptures	Hemorrhagic Kidneys	Eardrum Ruptures
36	322 (35.2) [0.246]	6	5 Extensive (1.08)	3	3	2 Bilateral
54	207 (19.8) [0.162]	6	3 Slight (0.68)	None	None	1 Unilateral
83	128 (9.2) [0.106]	6	1 Trace (0.75)	None	None	None
110	91 (5.7) [0.082]	9	None (0.69)	None	None	None

All charges were 1 lb.

Lung weight of eight controls was 0.65 (0.48–0.87) percent of body weight.

DISCUSSION

Blast Criteria for Mammals

Underwater-blast criteria for aquatic and marine mammals based on the results of this study are listed in table 10. They apply to sublethal conditions. An impulse of 40 psi·msec would result in a high incidence of moderately severe immersion-blast injuries including a high probability of eardrum rupture. The animals should recover on their own. An impulse of 20 psi·msec would cause slight blast injuries and a high incidence of eardrum rupture. An impulse of 10 psi·msec would result in a low incidence of trivial blast injuries and no eardrum rupture. An impulse of 5 psi·msec should not cause any injury and can be considered a safe one for mammals.

The above blast criteria should be safe-sided for animals at the surface. However, mammals on the surface may not gain as much protection from the underwater shock as do birds, because they displace more water and their lungs are more ventrally located.

Blast Criteria for Birds

Table 11 presents suggested criteria for birds diving beneath the water surface. The mortality threshold (LD_1) was 36 psi·msec. Most of the birds which survive this impulse level would appear unhurt but would sustain internal injuries of moderate severity--they should recover on their own. At higher impulses, the mortality rate climbs sharply as does the severity of injuries. The survivors may not recover on their own in the wild. Beyond the LD_1 impulse range, the severity and incidence of blast injuries could be expected to decrease rapidly. At 20 psi·msec, there would be slight lung injuries in half the cases and about a 50 percent probability of eardrum rupture. An impulse of 10 psi·msec was associated with little or no injury and no eardrum rupture. A no-effect or safe impulse was 6 psi·msec.

As already mentioned, birds on the water surface were relatively unaffected by the underwater explosions because the location of their vulnerable organs puts

TABLE 10. UNDERWATER - BLAST CRITERIA FOR MAMMALS DIVING BENEATH THE WATER SURFACE

Impulse, psi·msec	Criteria
40	No mortality. High incidence of moderately severe blast injuries including eardrum rupture. Animals should recover on their own.
20	High incidence of slight blast injuries including eardrum rupture. Animals would recover on their own.
10	Low incidence of trivial blast injuries. No eardrum ruptures.
5	Safe level. No injuries.

TABLE 11. UNDERWATER - BLAST CRITERIA FOR BIRDS DIVING BENEATH THE WATER SURFACE

Impulse, psi-msec	Criteria
45	50% mortality. Survivors seriously injured and might not survive on their own.
36	Mortality threshold (LD_1). Most survivors; moderate blast injuries and should survive on their own.
20	No mortality. Slight blast injuries and a low probability of eardrum rupture.
10	Low probability of trivial lung injuries and no eardrum rupture.
6	Safe level. No injuries.

them at least partially above the water line. Consequently, the surface birds represent a special case and require specific criteria as listed in Table 12. The impulses listed apply to those occurring at a 3-inch depth. The mortality threshold was on the order of 100 to 120 psi·msec. For impulse levels above and below these levels, the same remarks stated above for birds beneath the surface should apply. A safe impulse for birds on the water surface was taken as 30 psi·msec.

Impulse in Relation to Range and Charge Weight

Figure 20 presents a family of curves giving the ranges at which given impulses will occur. It takes into account the weight of the charge, depth of burst, and depth of the biological subject. To enter the graph, first calculate the quantity depth of charge x depth of subject/charge weight$^{2/3}$. Second, calculate the scaled impulse/charge weight$^{1/3}$. Third, read off the scaled slant range on the Y axis where the impulse intersects the curve. Divide the scaled range by the cube root of the charge weight to get the slant range. An example follows: Wanted: the slant range from a 2,000-pound charge, depth of burst 80 feet, where 6 psi·msec would occur at a depth of 20 feet. First solve the quantity:

$$\text{Depth of Charge x Depth of Subject/Charge Weight}^{2/3}$$

$$80 \times 20/2{,}000^{2/3} = 10$$

Second solve:

$$\text{Impulse/Charge Weight}^{1/3}$$

$$6/2{,}000^{1/3} = 0.5$$

Third, read the scaled slant range of 280 on the Y axis where 0.5 on the X axis intercepts the curve for 10:

$$\text{Scaled slant range} = \text{Slant range/charge weight}^{1/3}$$

$$280 \times 12.6 = 3{,}528 \text{ ft}$$

Figures 21 and 22 give isoimpulse curves of 36 and 6 psi·msec corresponding to mortality threshold and safe levels for birds beneath the surface in relation to slant range and the product of the depth of charge x depth of subject. The curves were calculated from Figure 20 for charge weights from 1 pound to 10^6 pounds.

TABLE 12. UNDERWATER-BLAST CRITERIA FOR BIRDS ON THE WATER SURFACE

Impulse, psi·msec	Criteria
130–150	50% mortality. Survivors seriously injured and might not survive on their own.
190–120	Mortality threshold (LD_1). Most survivors; moderate blast injuries and should survive on their own.
40–60	No mortality. Slight blast injuries.
30	Safe level. No injuries.

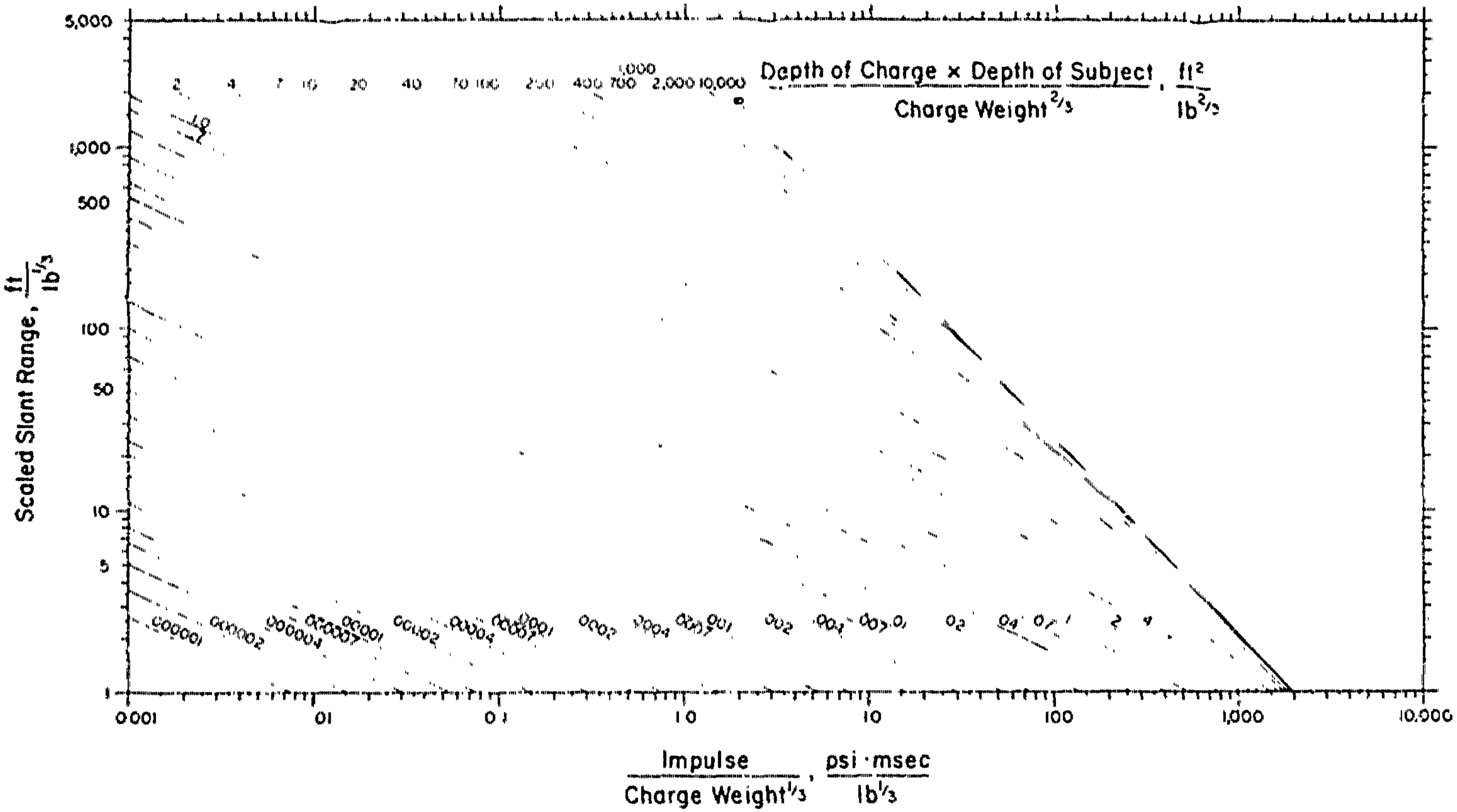


Figure 20. Curves for use in calculating ranges for various impulses.

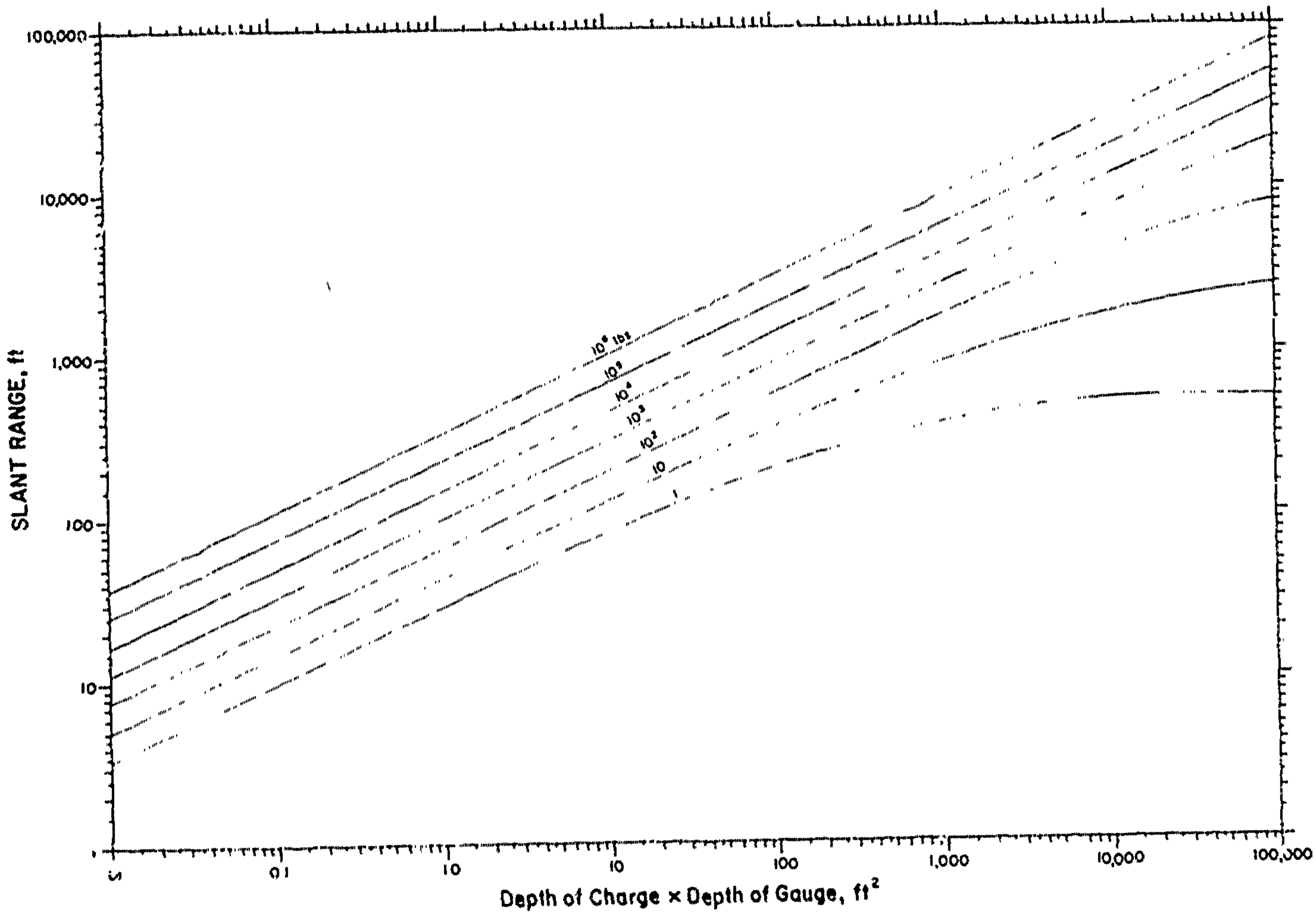


Figure 21. *Mortality threshold impulse curves for birds beneath the surface.*

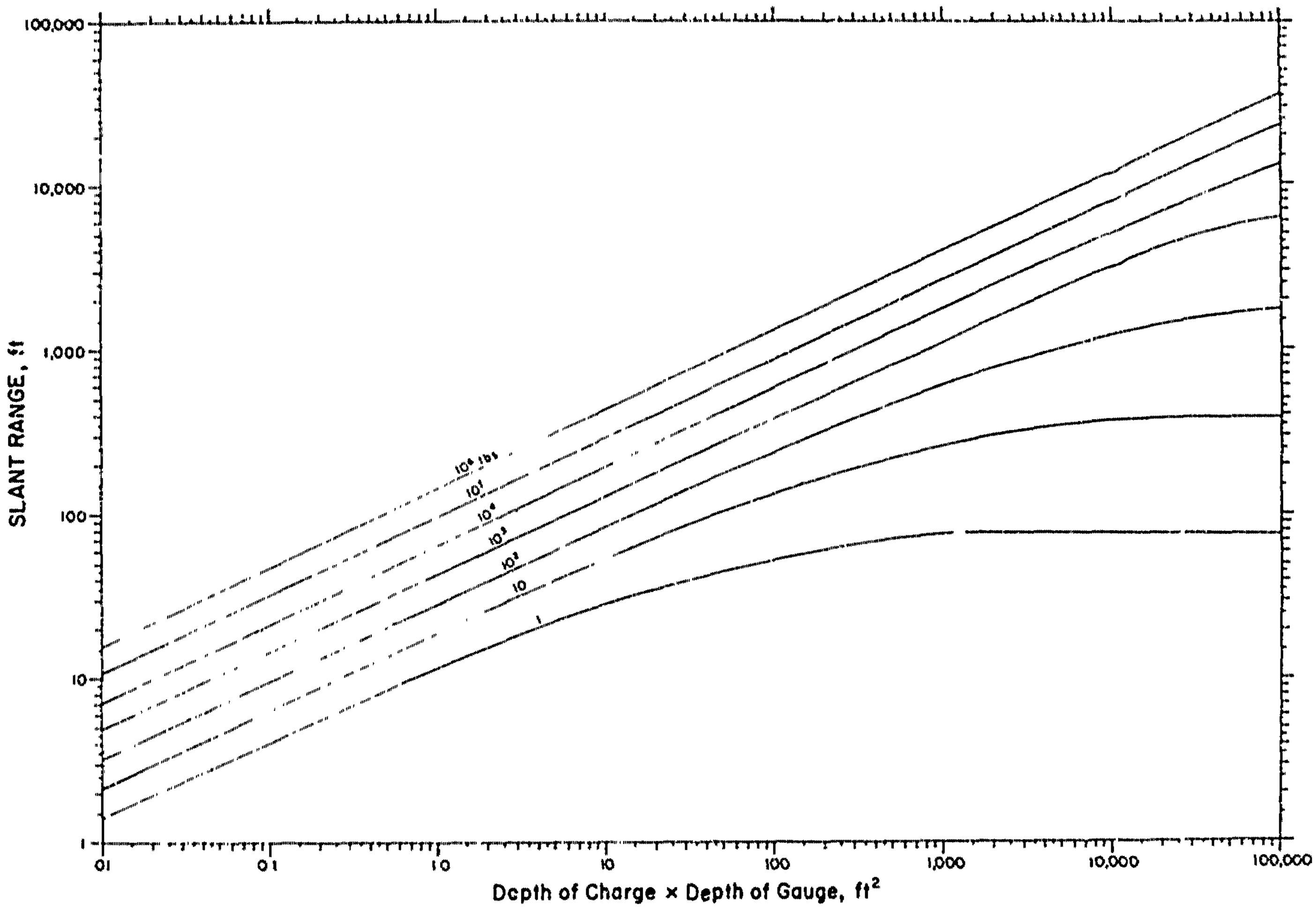


Figure 22. Safe impulse curves for birds and mammals beneath the surface.

The safe impulse for birds, for all practical purposes, can be applied to be the safe one for diving mammals.

Application of Blast Criteria

It seems reasonable to apply the information gathered on the effects of underwater shock with terrestrial mammals to the blast criteria for diving mammals. It has been established that the vulnerability of invertebrate animals to underwater blast depends on whether or not gas was present in their bodies. In mammals, the organs most damaged were those containing gas. Since the diving mammals possess lungs which certainly contain gas, their tolerance to underwater shock should not be importantly different from those used in the present study.

It should be mentioned here that the blast criteria should apply to a relatively large range of species size. The mammals used in this study were 5 kg monkeys, 15 to 20 kg dogs, and 40 kg sheep--yet their tolerance to the underwater shock was about the same. Any variation encountered probably was related more to the amount and distribution of gas in the G.I. tract than to the animal's size.

The criteria likewise should apply to a rather wide range of bird sizes. The results of recent tests showed that the LD_{50} air blasts for chickens, body weights about 1 kg, was the same as it was for small quail of 0.12 kg body weight.

It also should be mentioned that the criteria presented here may apply only to underwater shock waves generated by high explosives which have high detonation velocities like TNT, Pentolite, RDX, etc. These high explosives produce blast waves having a discontinuity at the leading edge. Animals should be more resistant to blast waves that rise to peak in several milliseconds, such as those produced by slower-burning explosives; i.e., black powder and dynamite.

That the impulse corresponds to the animal's underwater-blast dose better than does peak pressure or energy can be shown in the following sample of data. Three sheep at a 1-foot depth and at a slant range of 26 feet from a 1-pound charge sustained the same amount of G.I. tract damage as did three sheep at a 10-foot depth and at a slant range of 48 feet from a 1-pound charge.

The peak pressure was 478 psi at the 1-foot deep animals, and the energy was 2.32 in. lb/in^2. The peak pressure at the 10-foot deep animals was 269 psi, and the energy was 0.97 in·lb/in^2. The impulses were 42 psi·msec at the 1-foot deep animals and 45 psi·msec at the 10-foot deep ones. The impulses were nearly the same, yet the peak pressure and energy varied by a factor of about 2. It has been suggested that the underpressure was a factor in connection with fish kill from underwater explosion. The role, if any, played by the negative pressure in the far-field damage mechanism is not clear at this time.

Bottom Reflections

There are several reasons why bottom reflections encountered in the test pond were not significant in regard to adding to the underwater-blast dose that the animals received. First, based on the response of animals to air blasts having various waveforms (reference 5), the aberrant waveform of the bottom reflection over the ranges out to approximately 45 feet would not be expected to produce damage. Even though these impulses appear rather high in some instances (10 to 15 psi·msec), the associated peak pressures were low and the peak pressure was not at the leading edge of the wave. Beyond 50 feet, where the waves were more ideal-like, the peak pressures were low and, more importantly, the pulses were of short duration so that the impulses were small.

Second, if the bottom reflections were to add to the incident blast wave dose, there should have been an increase in the incidence of injuries at ranges from 40 to 60 feet where the reflected pressure waves were greater. However, the biological effects decreased over those ranges for targets at the 1-foot depths.

Third, some unpublished information exists in this laboratory suggesting that two pulses do not add to the damage unless they were delivered within a very short time--less than 2 msec. Furthermore, if these pulses were of low intensity, they were not additive even if delivered within a short time. In order to have an additive effect from two pulses, they had to be near lethal levels to begin with.

The fact that the bottom reflections were altered markedly from their classical waveforms was related to such factors as the reflected wave traveling through the disturbed water in and around the bubble pulse, the cavitation of the

water, the nature of the bottom, its angle of incident to the bottom, etc. These factors should be taken into account in applying the underwater-blast criteria.

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